National Nuclear Physics Summer School

Neutrino Physics
Lecture II
July 17, 2007

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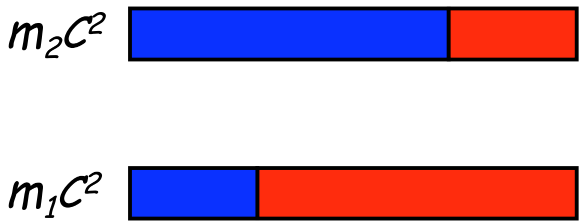
Berkeley

Essentials of Neutrino Oscillations



$$|\nu_e> = |\psi_{\nu_e}(0)> = \cos\theta\,|\nu_1> + \sin\theta\,|\nu_2>$$

$$|\psi_{\nu_e}(t)> = \cos\theta e^{-\frac{im_1c^2t}{\hbar}}\,|\nu_1> + \sin\theta e^{-\frac{im_2c^2t}{\hbar}}\,|\nu_2>$$

$$P_{ee}(t) = \left|<\psi_{\nu_e}(0)\,|\psi_{\nu_e}(t)>\right|^2 = \left|\cos^2\theta e^{-\frac{im_1c^2t}{\hbar}} + \sin^2\theta e^{-\frac{im_2c^2t}{\hbar}}\right|^2$$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar}t\right)$$

$$t = \frac{t_{lab}}{\gamma} \approx \frac{L}{\gamma c} \qquad \gamma = \frac{E}{mc^2} \qquad m = \frac{m_1 + m_2}{2}$$

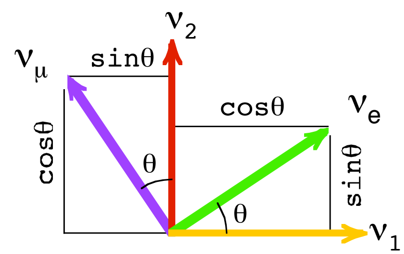
$$P_{ee}(L) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)c^4}{4\hbar c}\frac{L}{E}\right)$$

$$P_{ee}(L) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Бруно Понтекорво

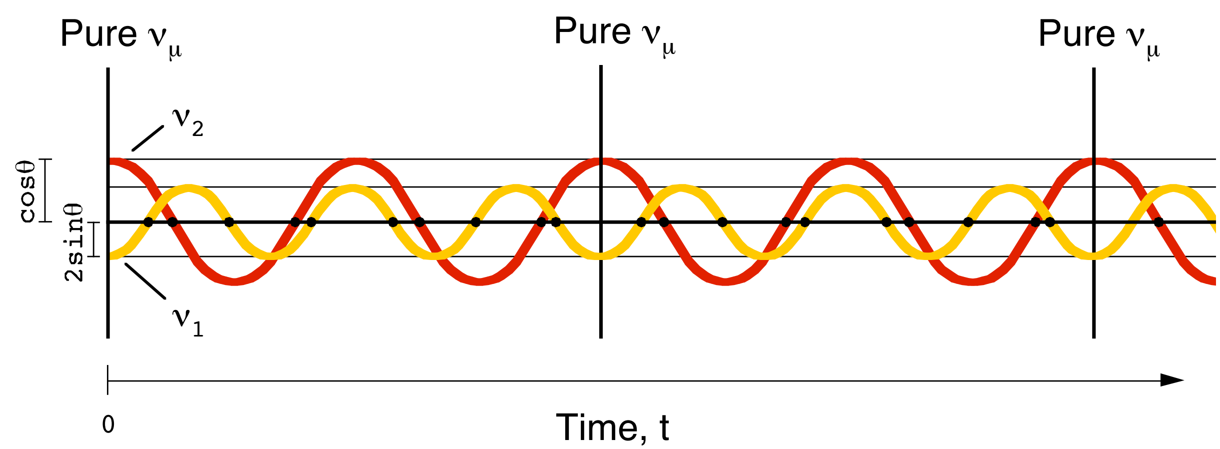
Neutrino Oscillations

Neutrino States



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

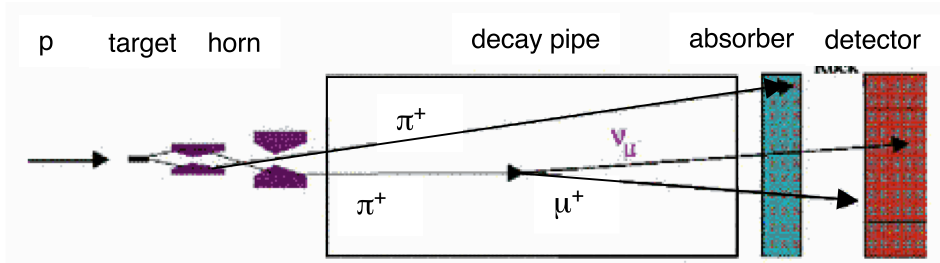
Time Evolution



$$P_{\mu e}(t) = \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

Neutrino Oscillation Experiments

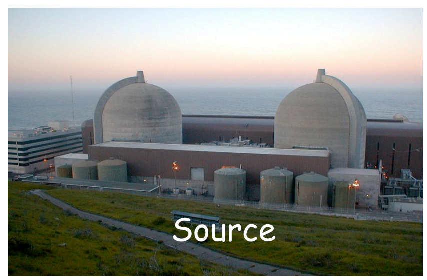
Appearance *Experiments* :



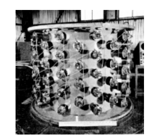
Produce one Flavor -- Look for another

$$P_{\mu e}(t) = \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

Disappearance *Experiments* :



Detector



Produce and detect the same flavor --Look a discrepancy from $1/R^2$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

Where do the neutrinos come from?

Natural Sources

Solar Neutrinos

^{37}Cl	Kamiokande
GALLEX	SuperKamiokande
SAGE	SNO

Atmospheric Neutrinos

IMB	Kamiokande
Soudan	SuperKamiokande
MACRO	…

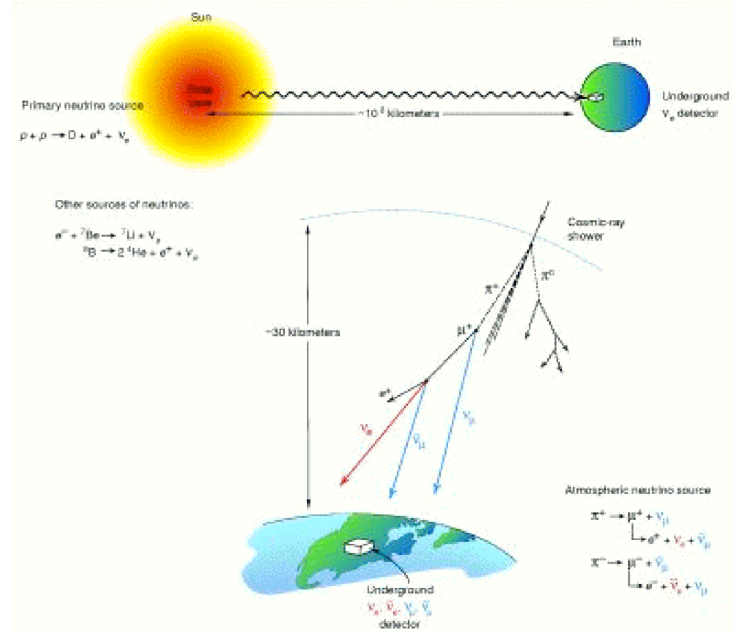
Man-Made Sources

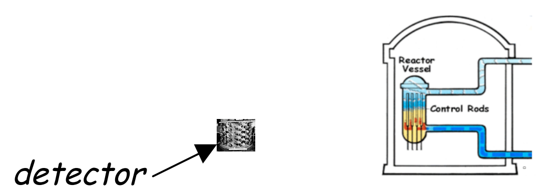
Accelerator Neutrinos

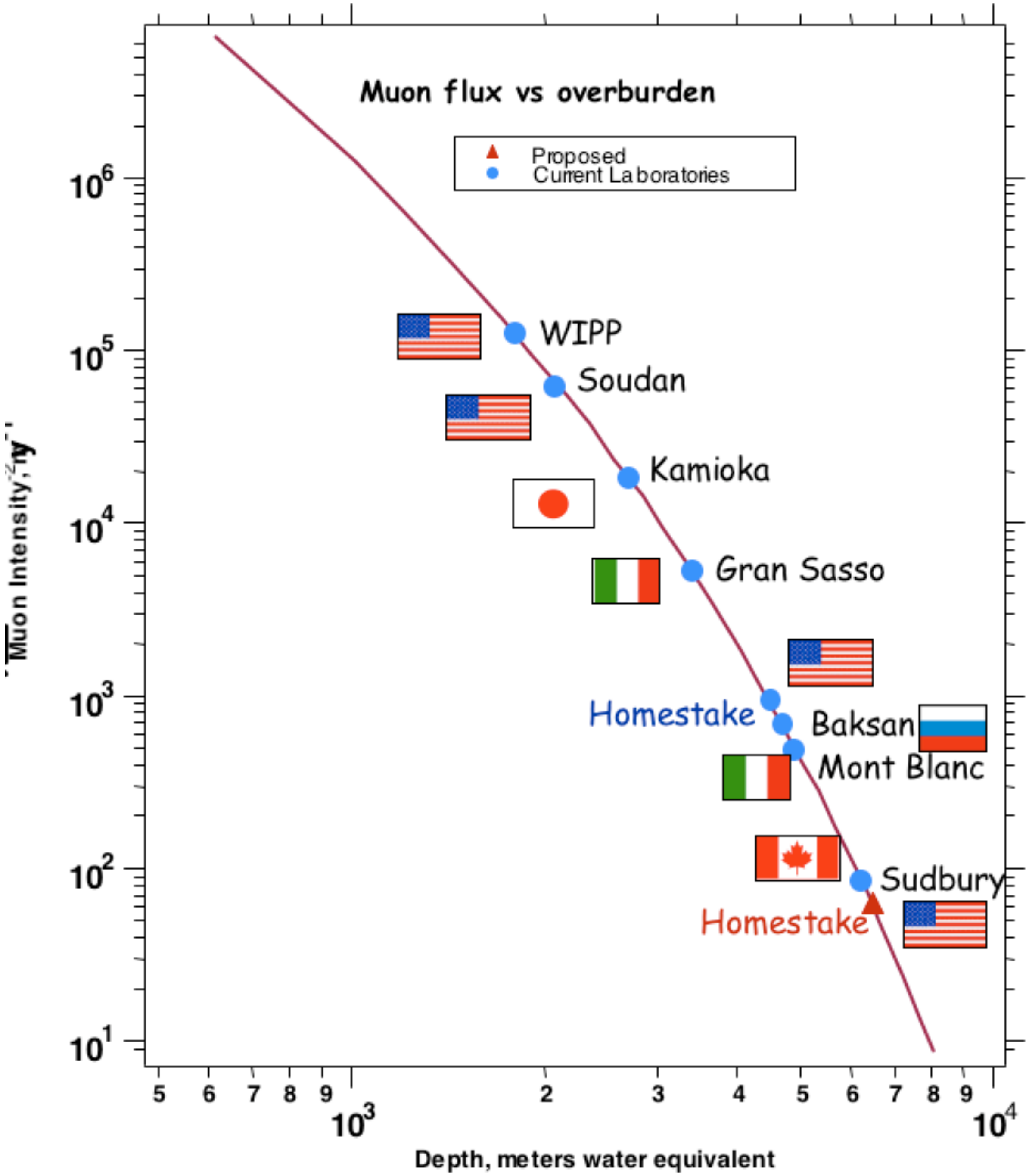
K2K	Chorus
Opera	LSND?
…	

Reactors Neutrinos

Bugey	Goesgen
ILL	Chooz
Palo Verde	KamLAND

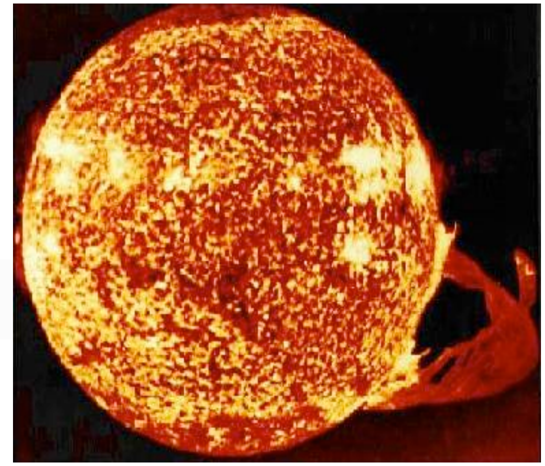




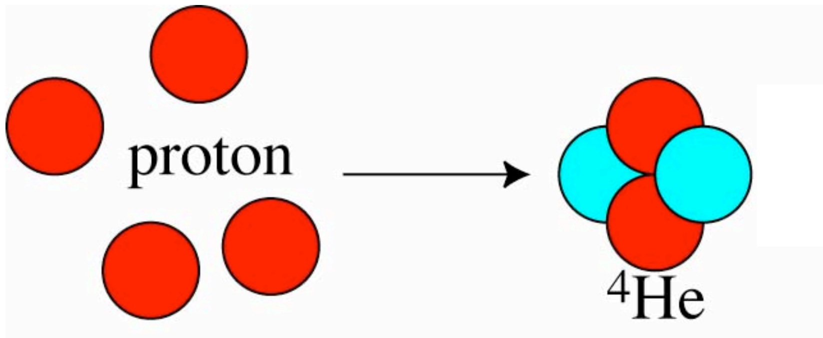


Muon flux vs overburden
Proposed
Current Laboratories
WIPP
Soudan
Kamioka
Gran Sasso
Homestake
Baksan
Mont Blanc
Sudbury
Homestake
Muon Intensity
Depth, meters water equivalent

Nuclear Burning



$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$



$$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 26.73 MeV - E_\nu$$

$$\langle E_\nu \rangle \sim 0.6 MeV$$

UNIT

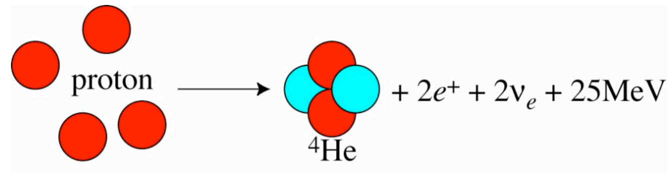
For Neutrino Detectors:

$$\text{RATE} = \sum(\text{FLUX}) \times (\text{CROSS SECTION})$$

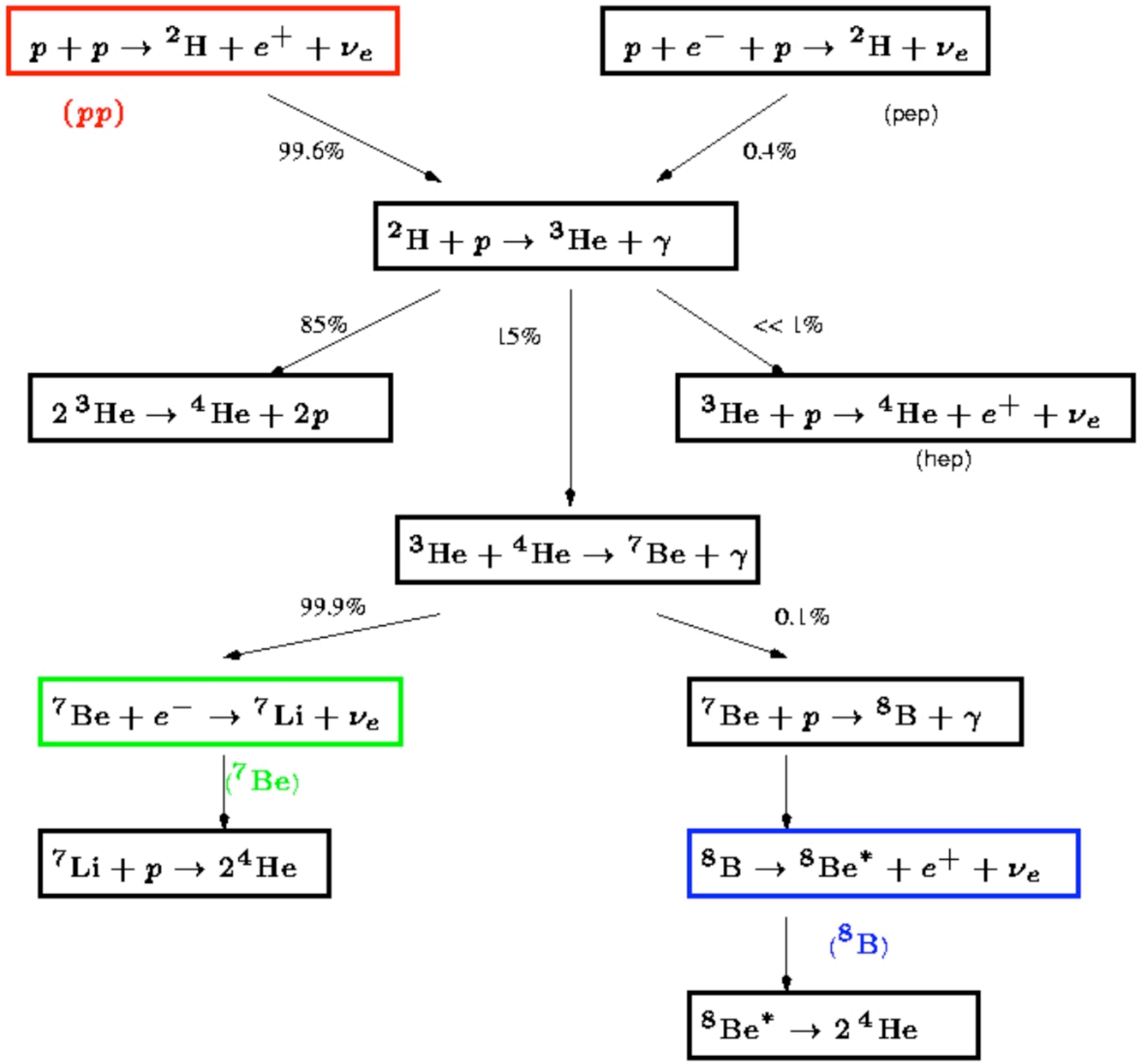
$$\sim 10^{10}\ \text{cm}^{-2}\text{s}^{-1} \times 10^{-46}\ \text{cm}^2$$

$$1\ SNU = 10^{-36}\ \text{INTERACTIONS PER TARGET ATOM PER SEC}$$

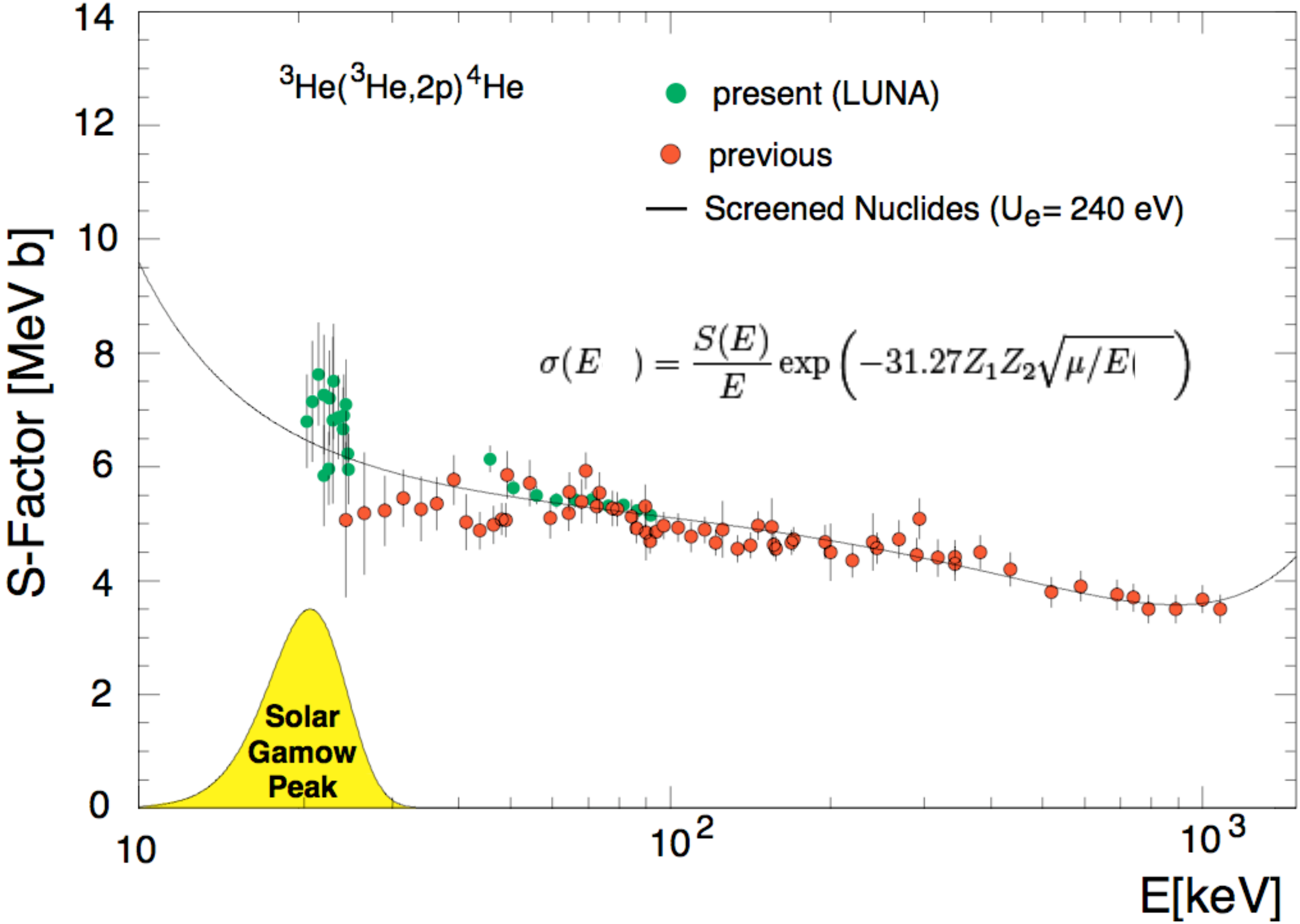
The *pp* Chain



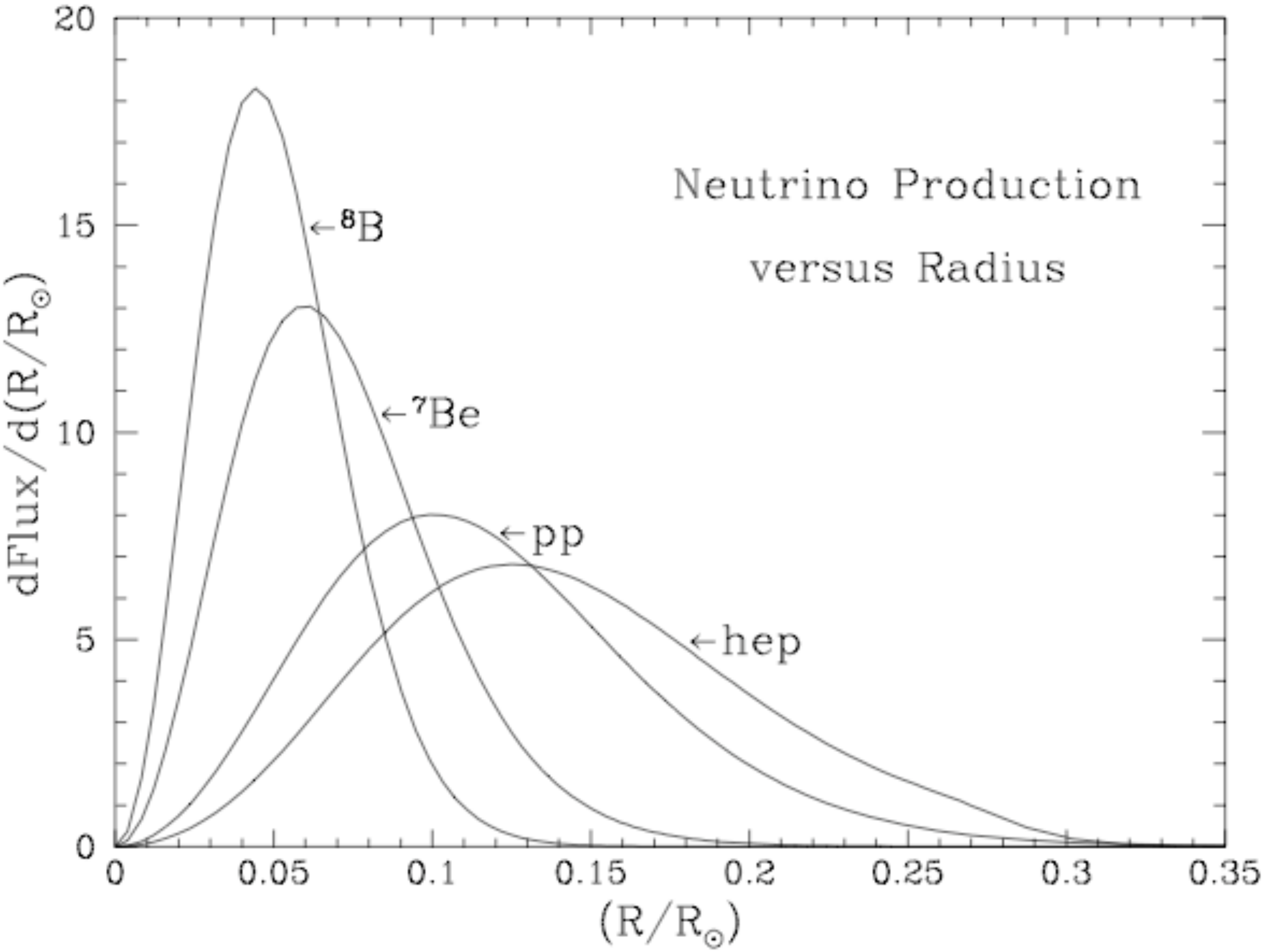
proton
$+ 2e^+ + 2\nu_e + 25\text{MeV}$
^{4}He

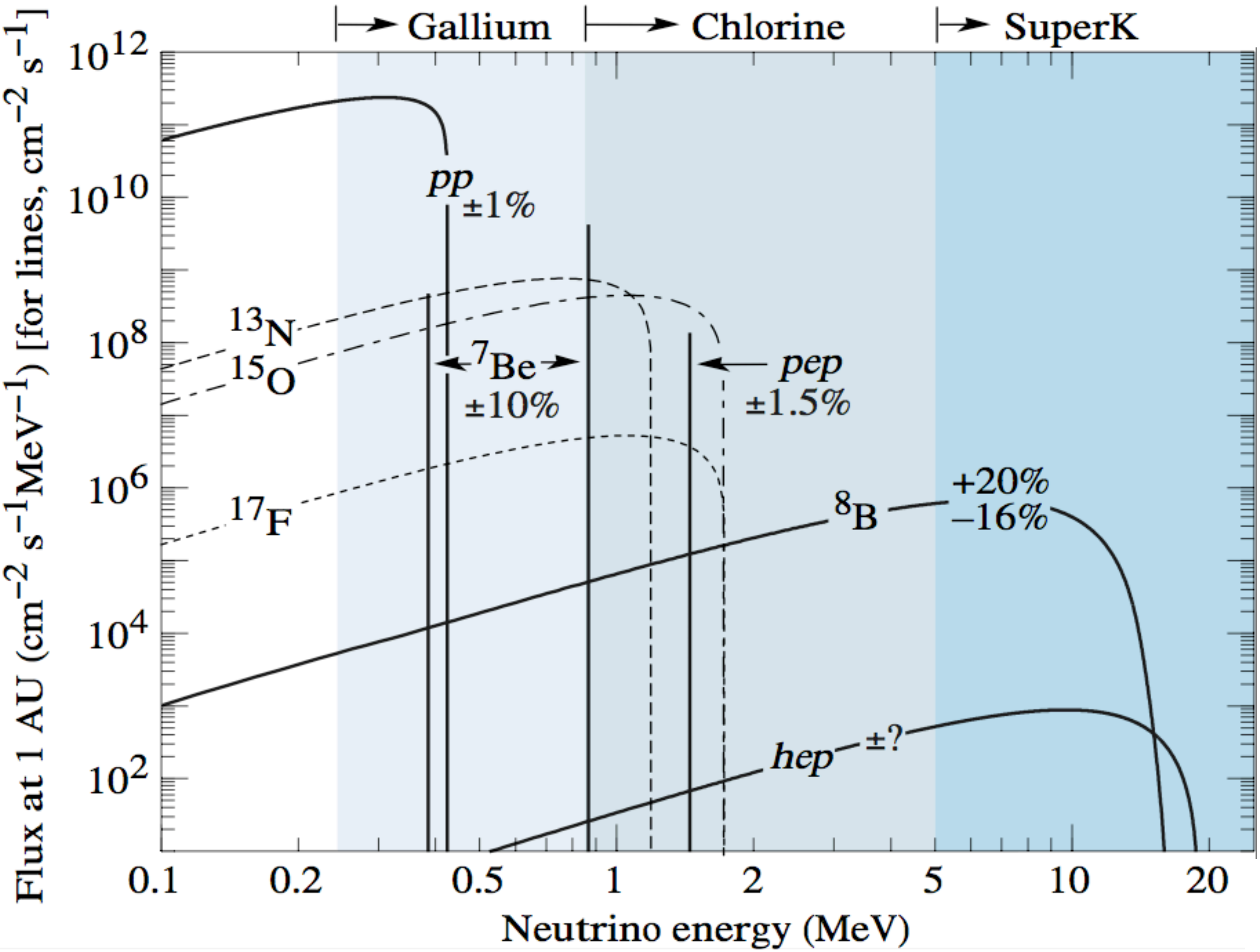


$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$
(pp)
$p + e^- + p \rightarrow {}^2\text{H} + \nu_e$
(pep)
99.6%
0.4%
${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$
85%
15%
<< 1%
$2\,{}^3\text{He} \rightarrow {}^4\text{He} + 2p$
${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$
(hep)
${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$
99.9%
0.1%
${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$
$({}^7\text{Be})$
${}^7\text{Li} + p \rightarrow 2\,{}^4\text{He}$
${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$
${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$
$({}^8\text{B})$
${}^8\text{Be}^* \rightarrow 2\,{}^4\text{He}$



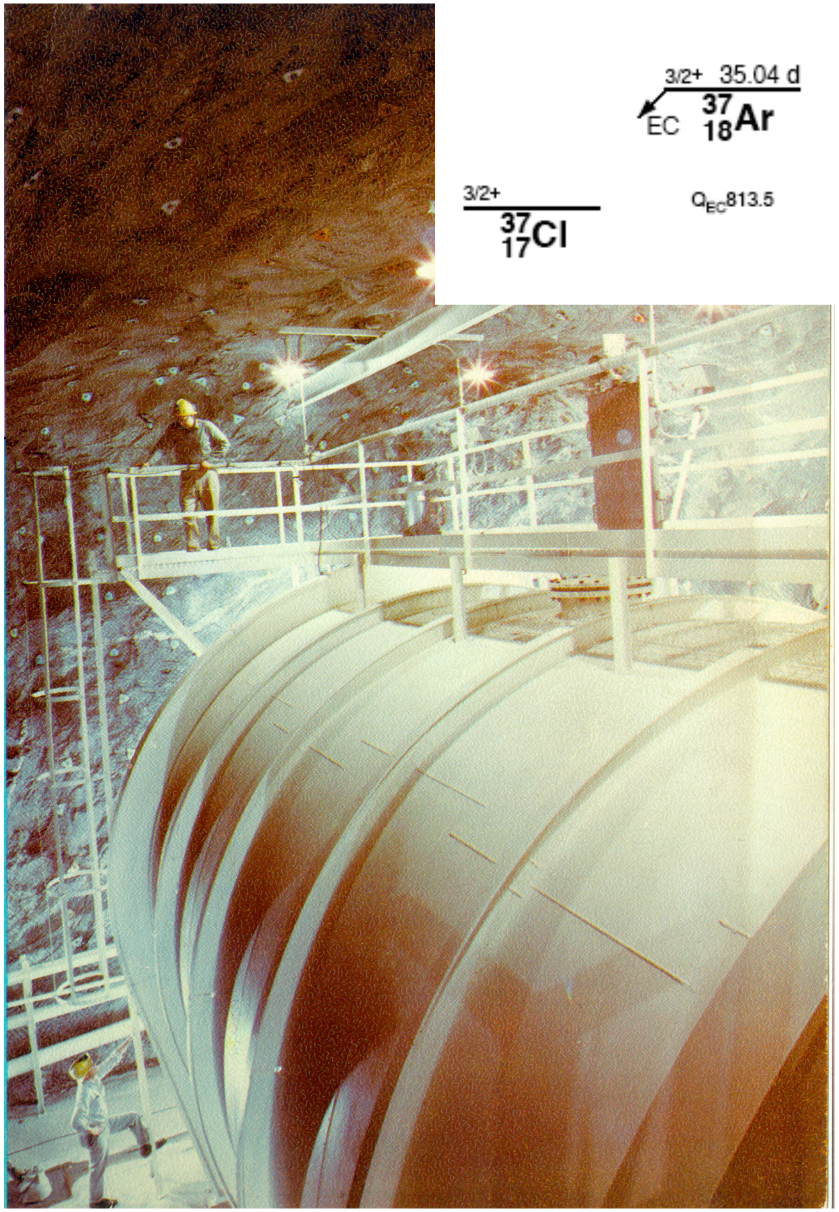
$^3He(^3He,2p)^4He$
present (LUNA)
previous
Screened Nuclides (U_e= 240 eV)
$\sigma(E) = \frac{S(E)}{E} \exp\left(-31.27 Z_1 Z_2 \sqrt{\mu/E}\right)$
Solar Gamow Peak
S-Factor [MeV b]
E[keV]


Neutrino Production
versus Radius
←^{8}B
←^{7}Be
←pp
←hep
dFlux/d(R/R$_\odot$)
(R/R$_\odot$)
0
5
10
15
20
0.05
0.1
0.15
0.2
0.25
0.3
0.35



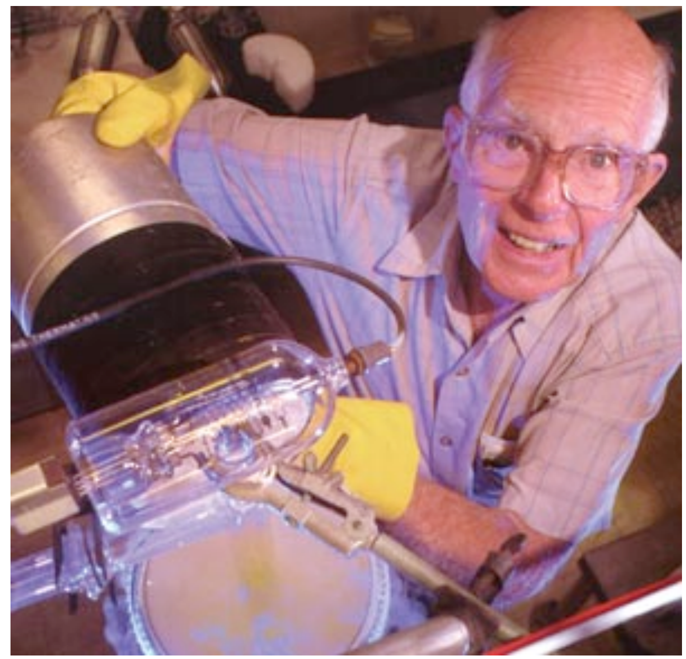
Gallium
Chlorine
SuperK
pp ±1%
13N
15O
7Be ±10%
pep ±1.5%
17F
8B +20% −16%
hep ±?
Flux at 1 AU (cm−2 s−1 MeV−1) [for lines, cm−2 s−1]
Neutrino energy (MeV)
0.1
0.2
0.5
1
2
5
10
20
10^12
10^10
10^8
10^6
10^4
10^2

Pioneering venture in Neutrino Physics



$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

$$^{37}Ar + e^- \rightarrow {}^{37}Cl^* + \nu_e$$



Ray Davis

Plan of Davis Experiment

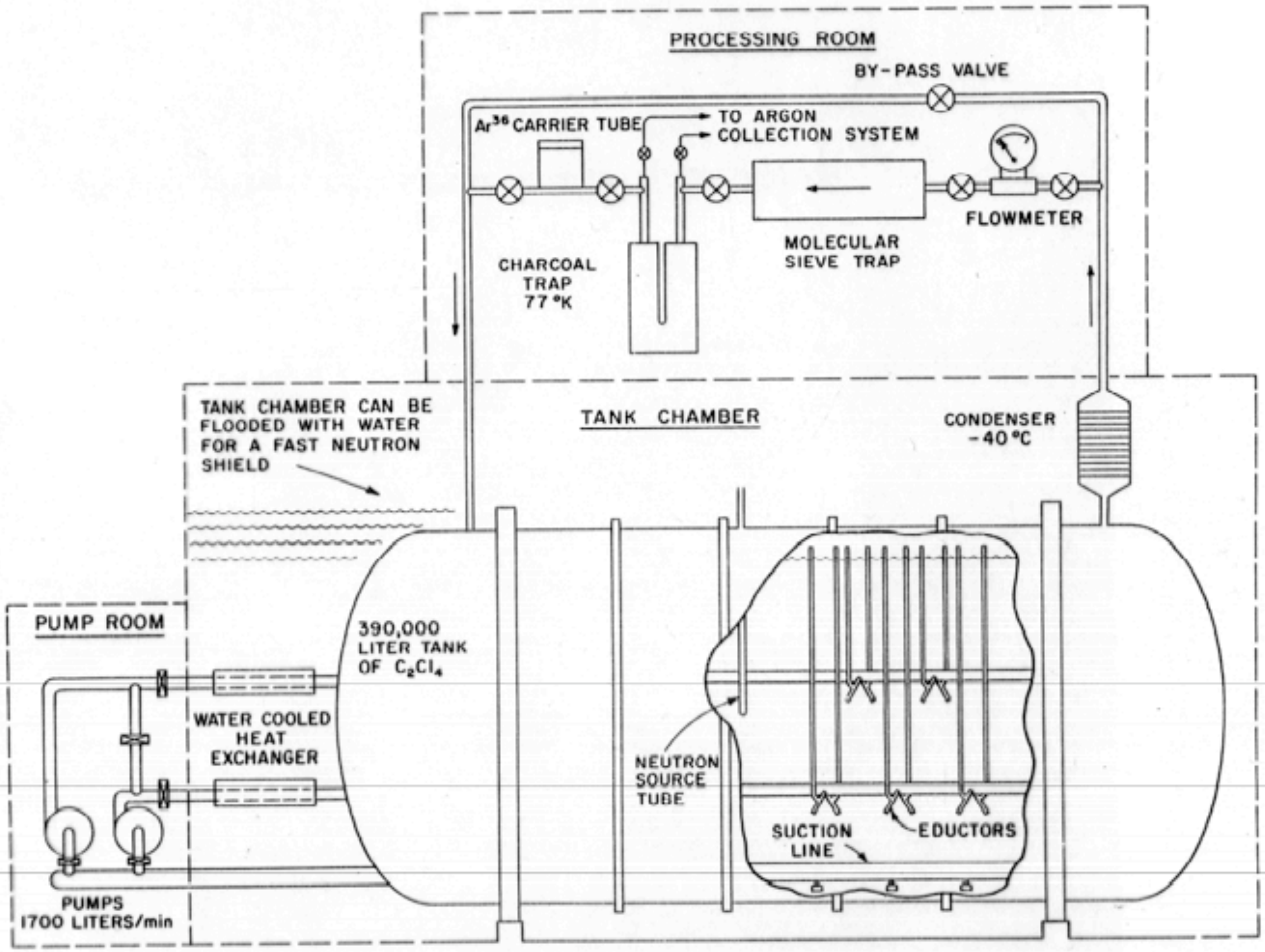
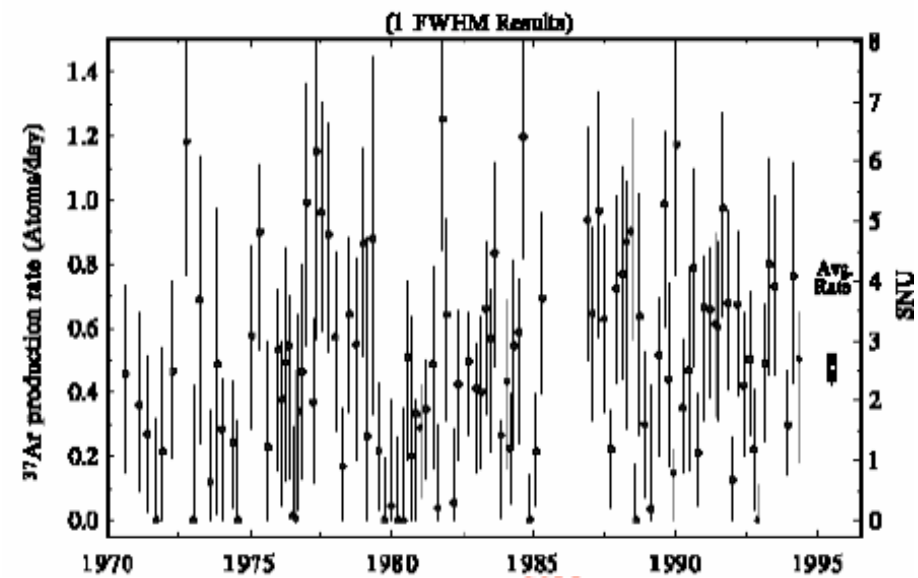
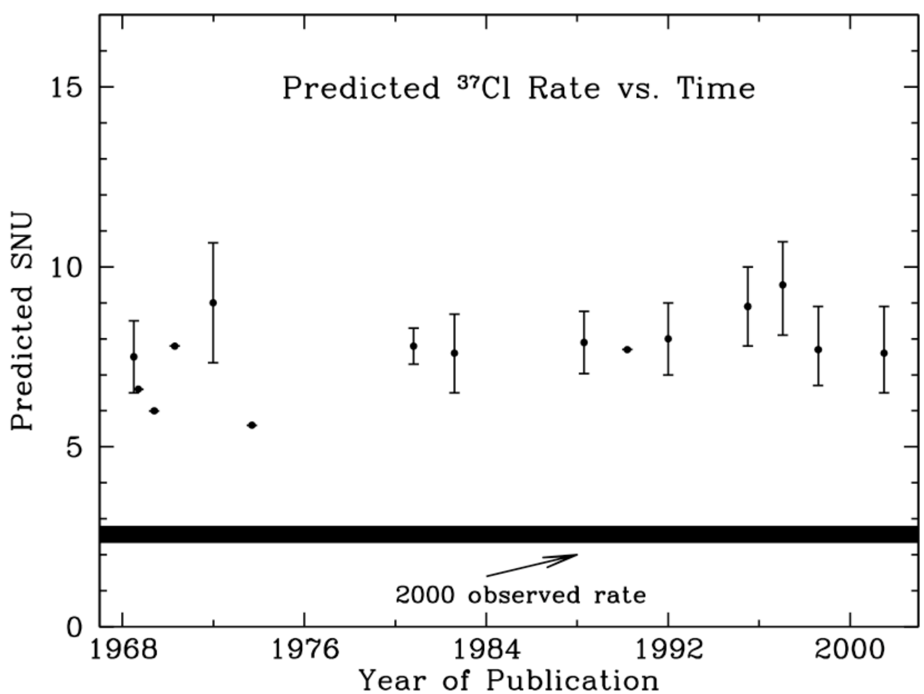


Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

Results

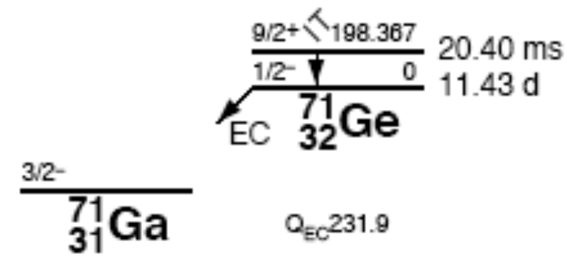

(1 FWHM Results)
^{37}Ar production rate (Atoms/day)
SNU
Avg. Rate
1970
1975
1980
1985
1990
1995

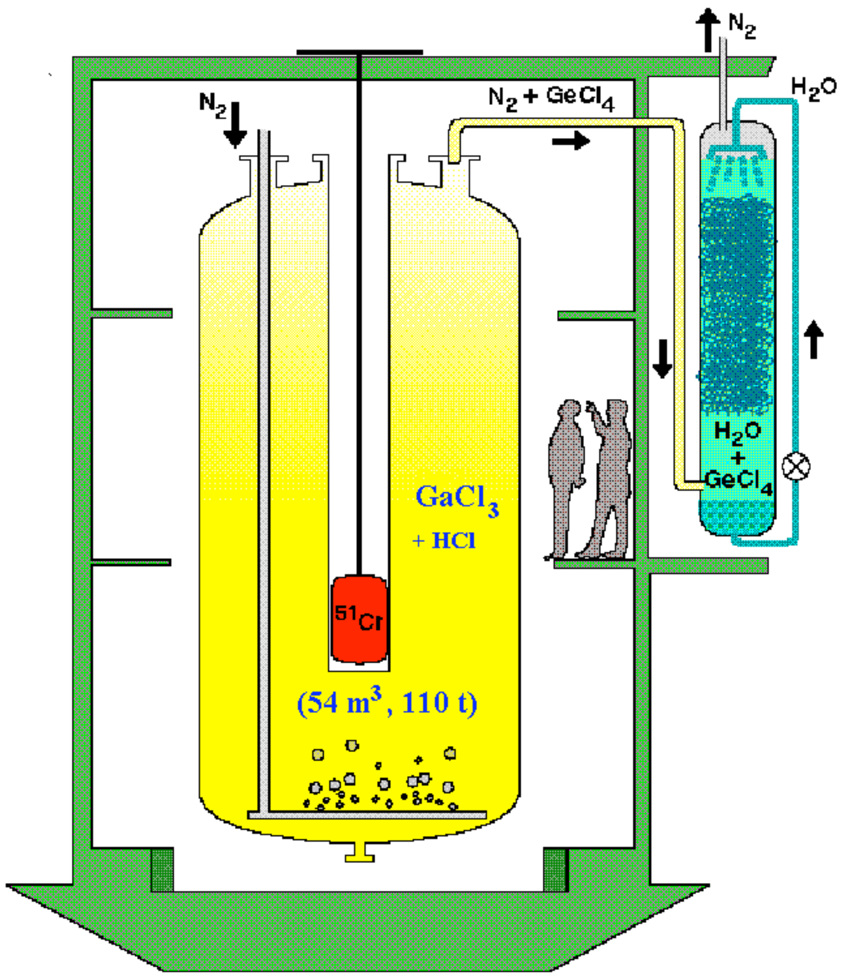

Predicted ^{37}Cl Rate vs. Time
Predicted SNU
2000 observed rate
Year of Publication

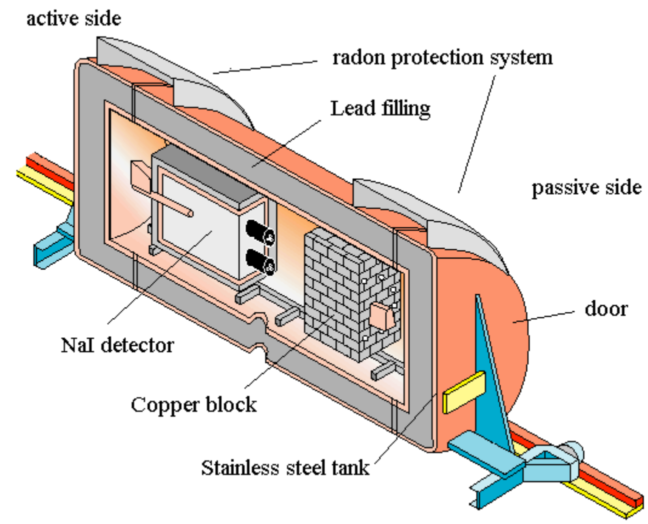
Gallex

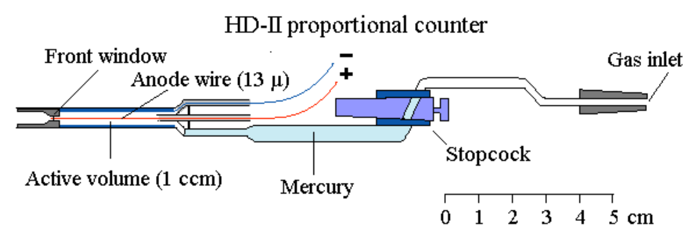
$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

$$^{71}Ge + e^- \rightarrow {}^{71}Ga^* + \nu_e$$

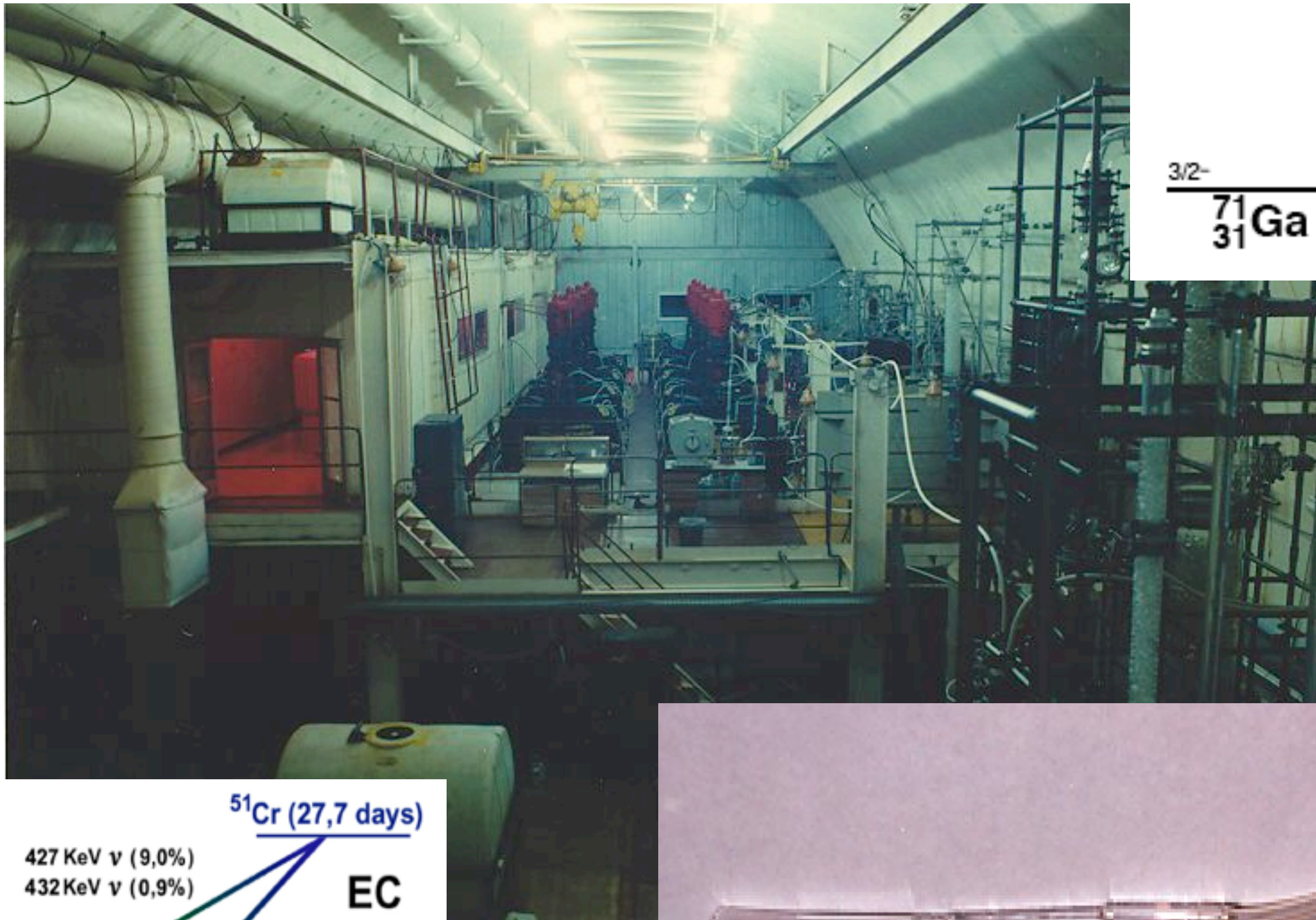


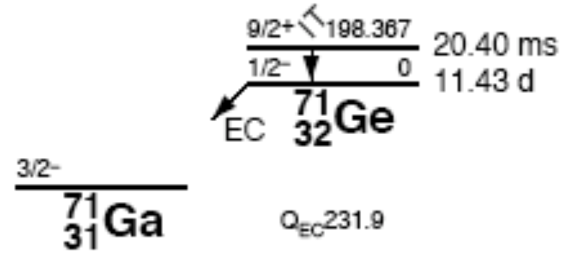


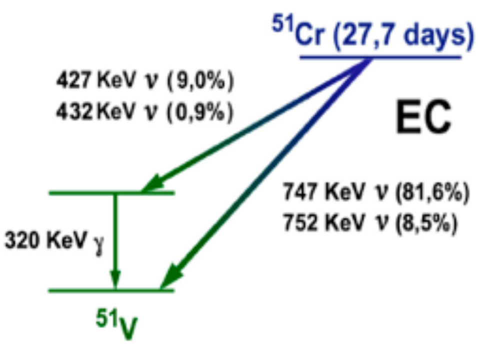


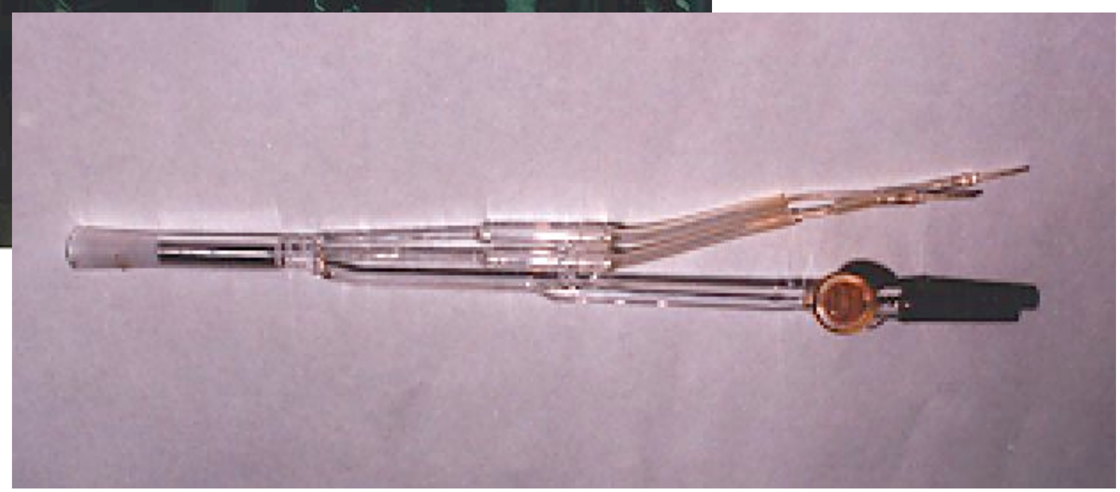


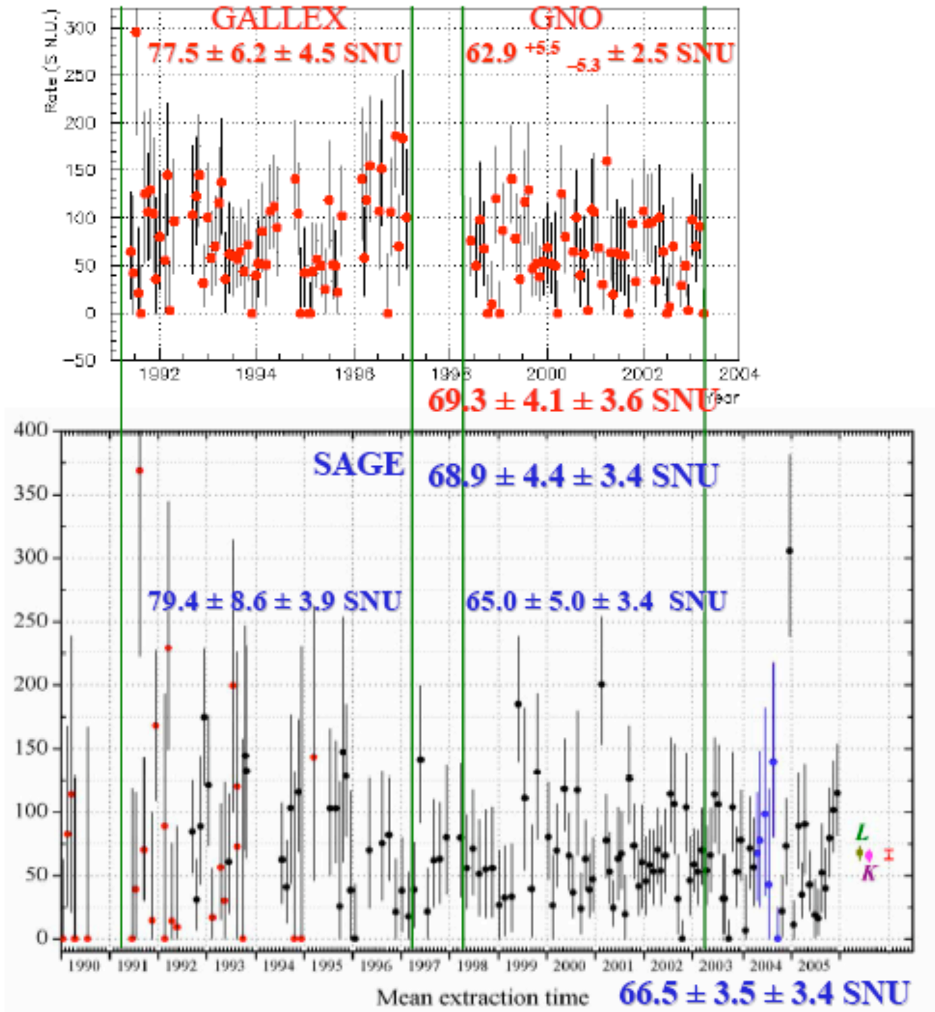
SAGE - ~~Soviet~~ Russian American Gallium Experiment





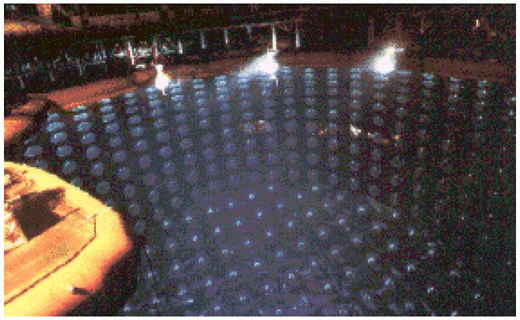




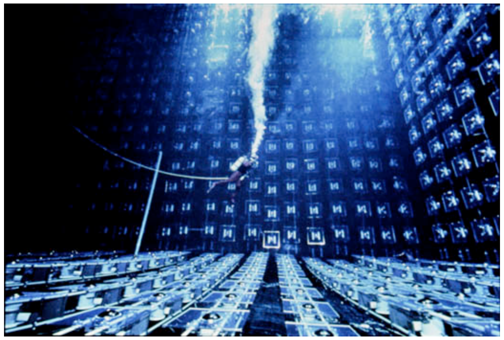


GALLEX
77.5 ± 6.2 ± 4.5 SNU
GNO
62.9 +5.5 −5.3 ± 2.5 SNU
Rate (S.N.U.)
Year
69.3 ± 4.1 ± 3.6 SNU
SAGE
68.9 ± 4.4 ± 3.4 SNU
79.4 ± 8.6 ± 3.9 SNU
65.0 ± 5.0 ± 3.4 SNU
Mean extraction time
66.5 ± 3.5 ± 3.4 SNU
L
K

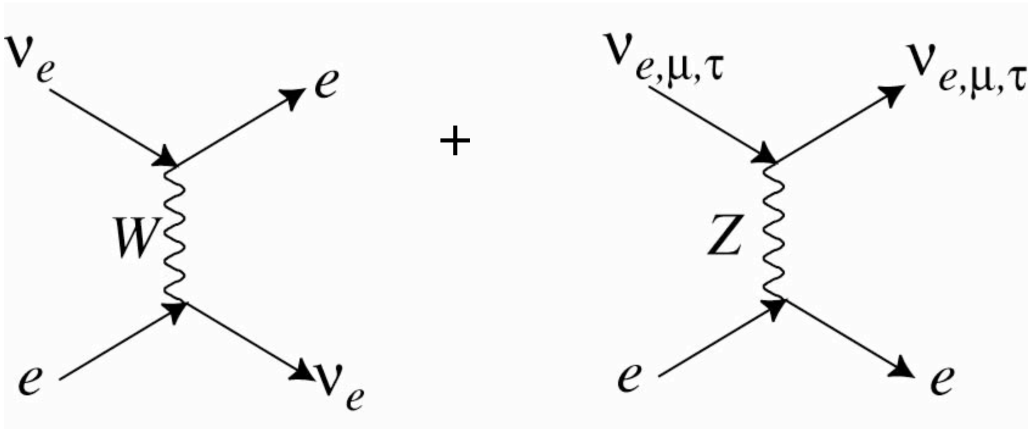
Ring-imaging water Cherenkov Detectors



KamiokaNDE



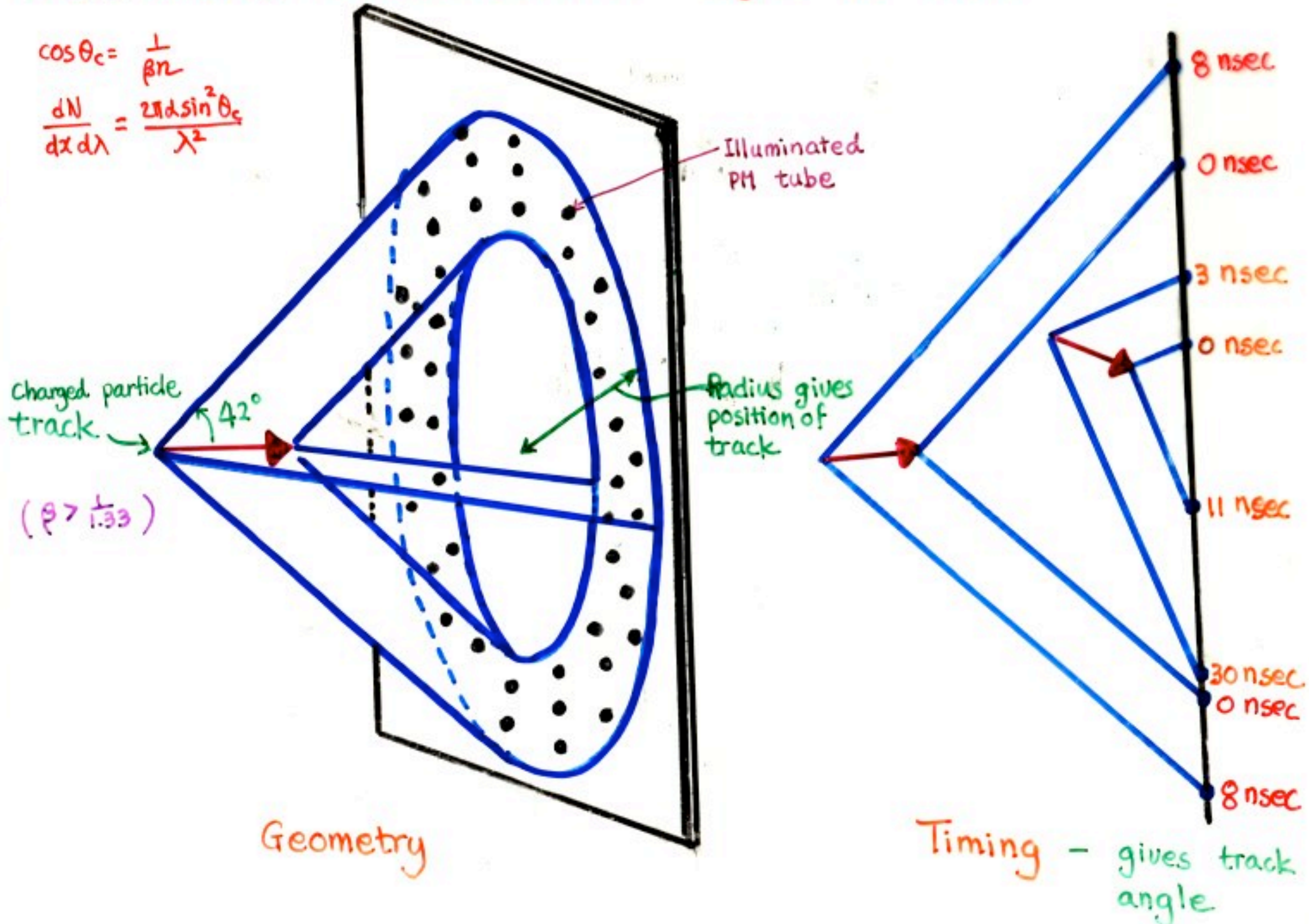
IMB



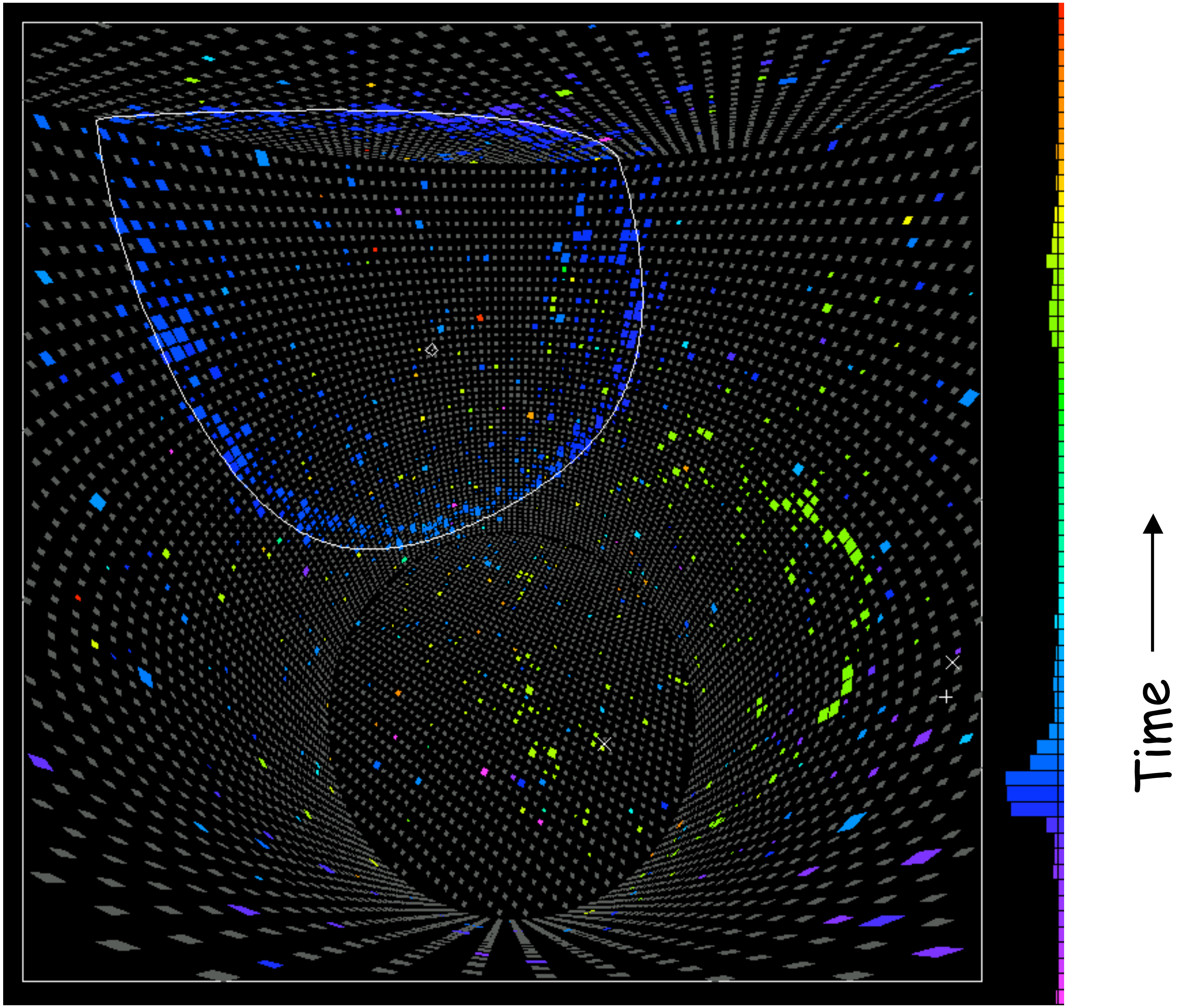
Basic Idea; Detect Cherenkov Light in Water

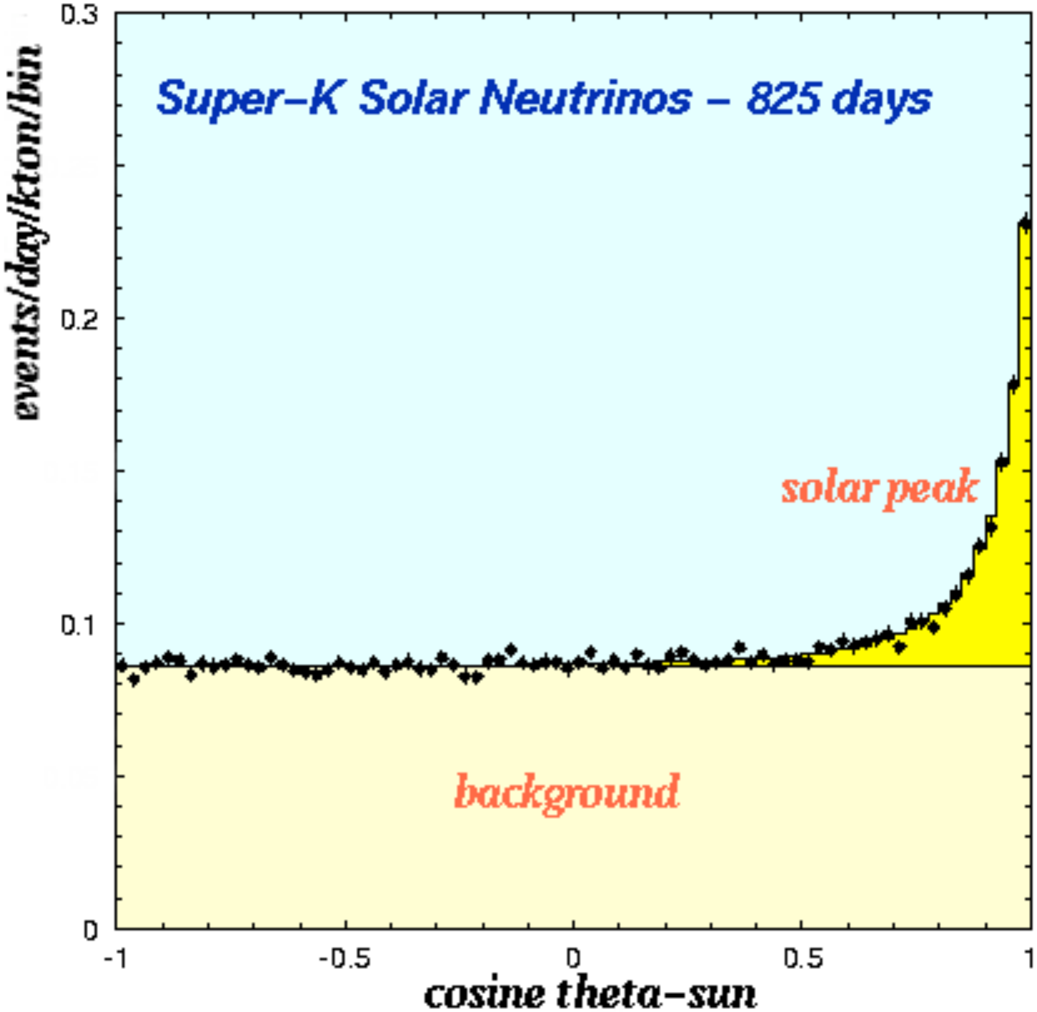
$$\cos\theta_c = \frac{1}{\beta n}$$

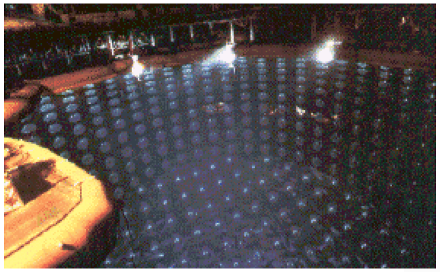
$$\frac{dN}{dx\,d\lambda} = \frac{2\pi\alpha \sin^2\theta_c}{\lambda^2}$$

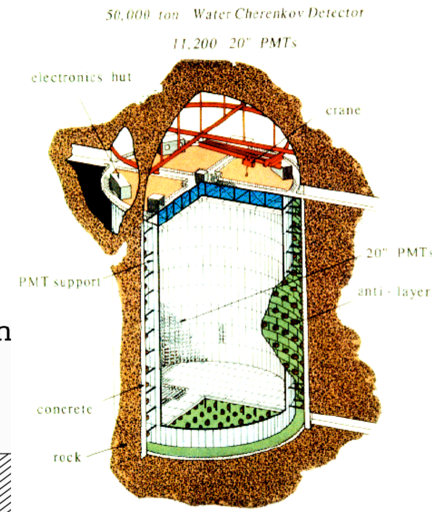


Probably $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

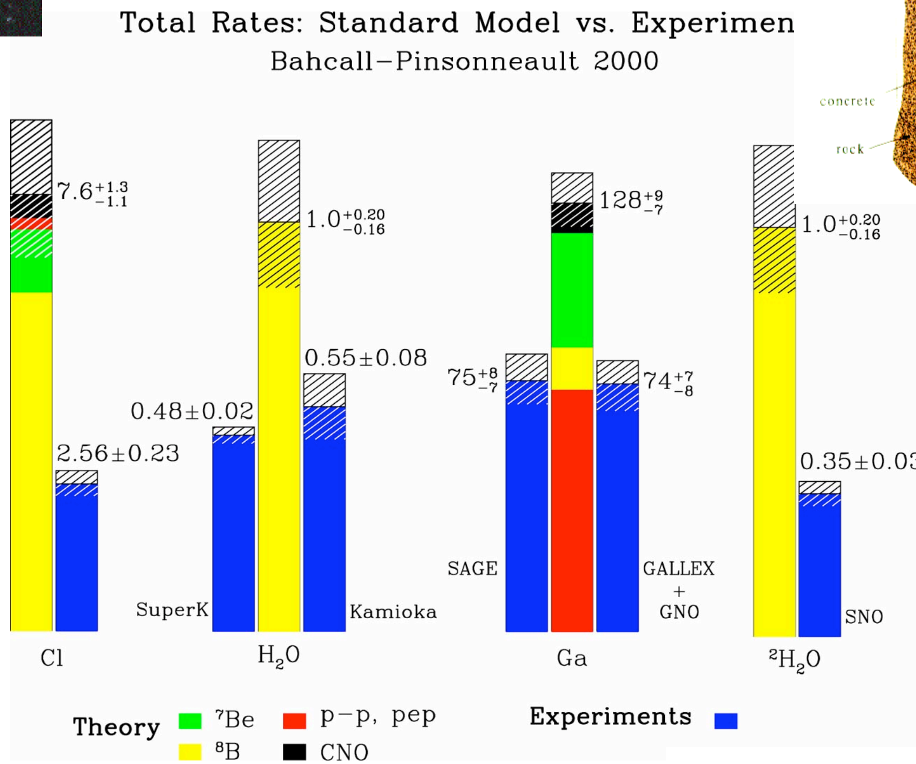



Super-K Solar Neutrinos – 825 days
events/day/kton/bin
solar peak
background
cosine theta-sun
0.3
0.2
0.1
0
-1
-0.5
0
0.5
1

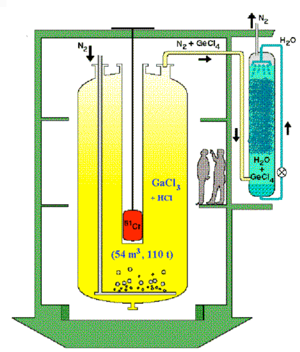


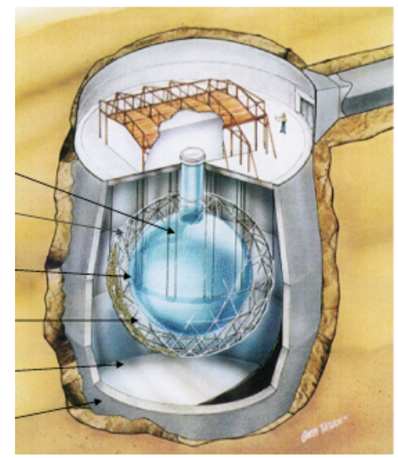


50,000 ton Water Cherenkov Detector
11,200 20" PMTs
electronics hut
crane
20" PMTs
PMT support
anti - layer
concrete
rock



Total Rates: Standard Model vs. Experimen
Bahcall−Pinsonneault 2000
$7.6^{+1.3}_{-1.1}$
2.56 ± 0.23
Cl
0.48 ± 0.02
$1.0^{+0.20}_{-0.16}$
0.55 ± 0.08
SuperK
Kamioka
H_2O
75^{+8}_{-7}
128^{+9}_{-7}
74^{+7}_{-8}
SAGE
GALLEX + GNO
Ga
$1.0^{+0.20}_{-0.16}$
0.35 ± 0.03
SNO
^2H_2O
Theory
^{7}Be
p−p, pep
^{8}B
CNO
Experiments





Vacuum Oscillations

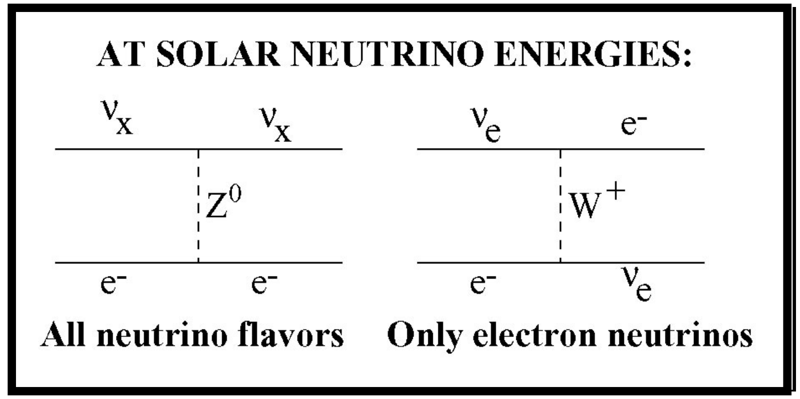
$$i\hbar \frac{d}{dt}\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix}\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta\end{bmatrix}$$

$$P(\nu_e \rightarrow \nu_x) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$$\Delta m_{ij}^2 \equiv (m_i^2 - m_j^2)$$

Matter Oscillations



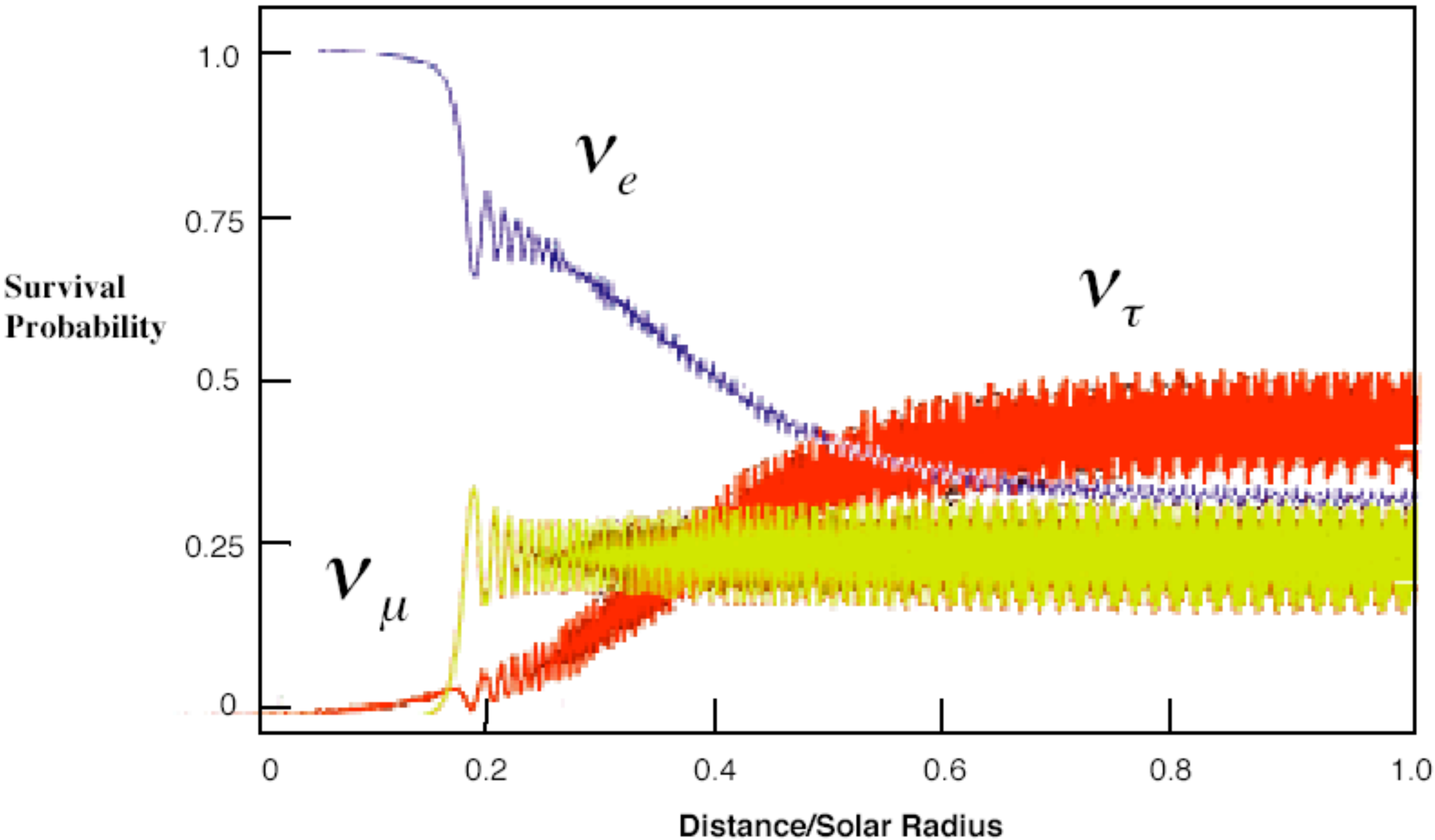
$$i\hbar \frac{d}{dt}\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix} \frac{\Delta m^2}{4E}\cos 2\theta - \sqrt{2}G_F\rho_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - \sqrt{2}G_F\rho_e E/\Delta m^2)^2 + \sin^2 2\theta}$$

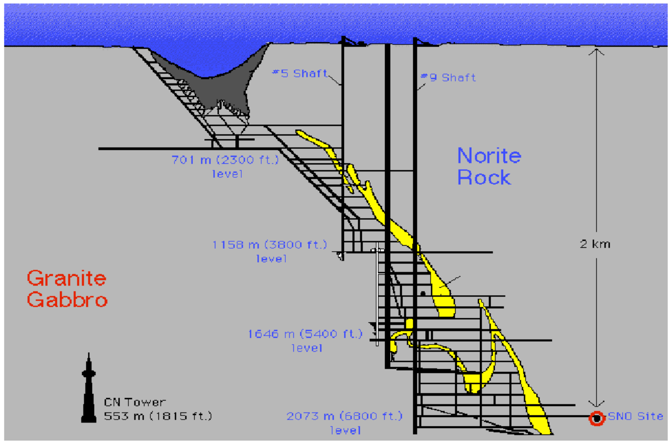
$$\Delta m_{ij}^2 \equiv (m_i^2 - m_j^2)$$

MSW Effect



Rosen

Sudbury Neutrino Observatory



1000 tonnes D_2O

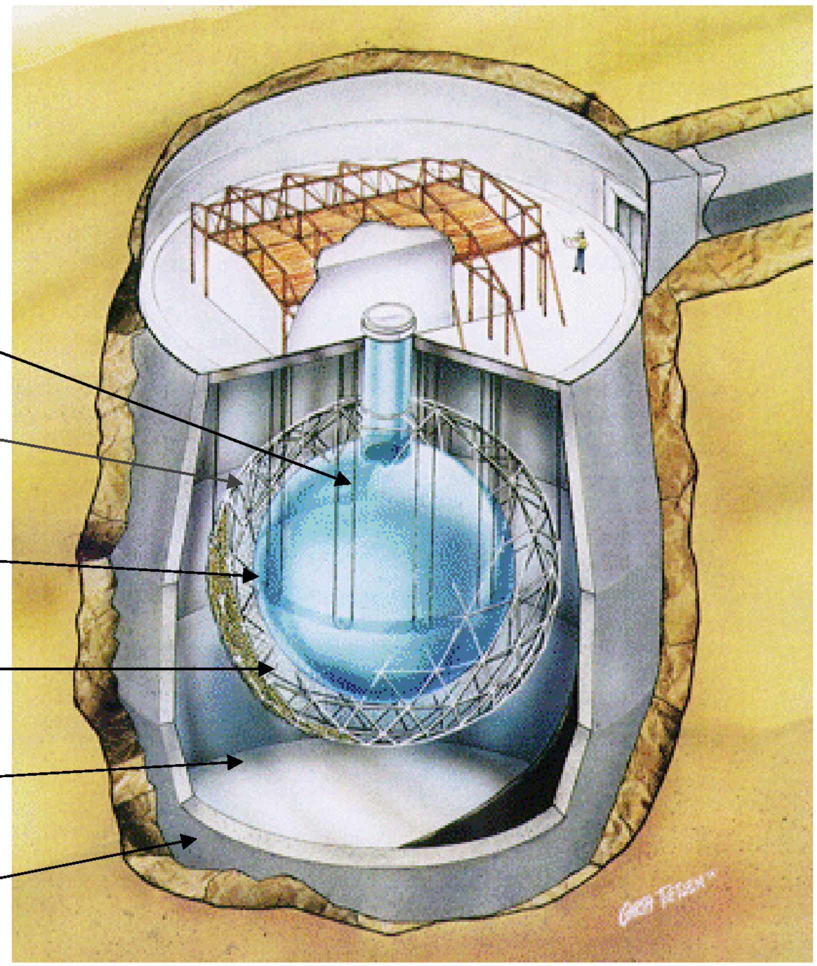
Support Structure for 9500 PMTs, 60% coverage

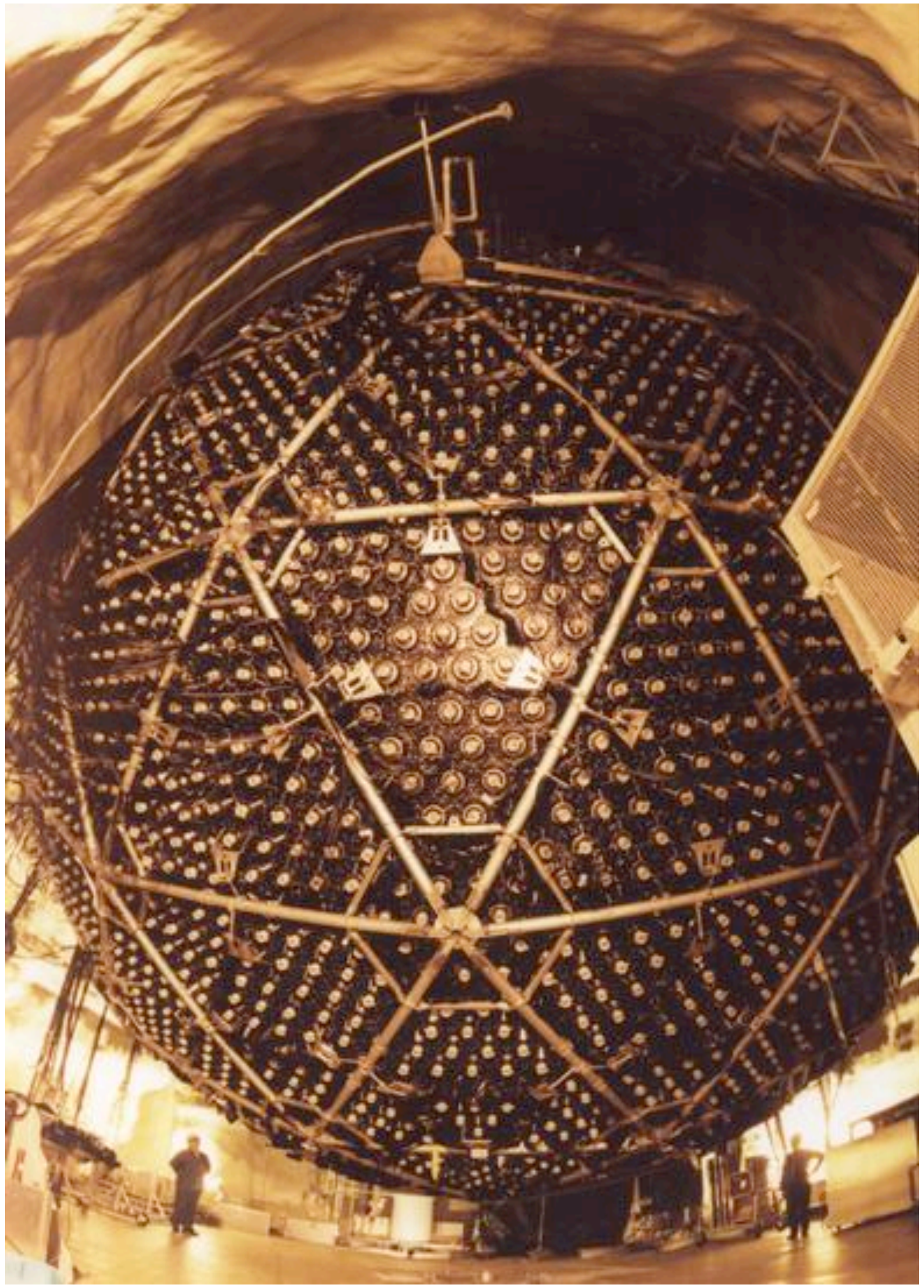
12 m Diameter Acrylic Vessel

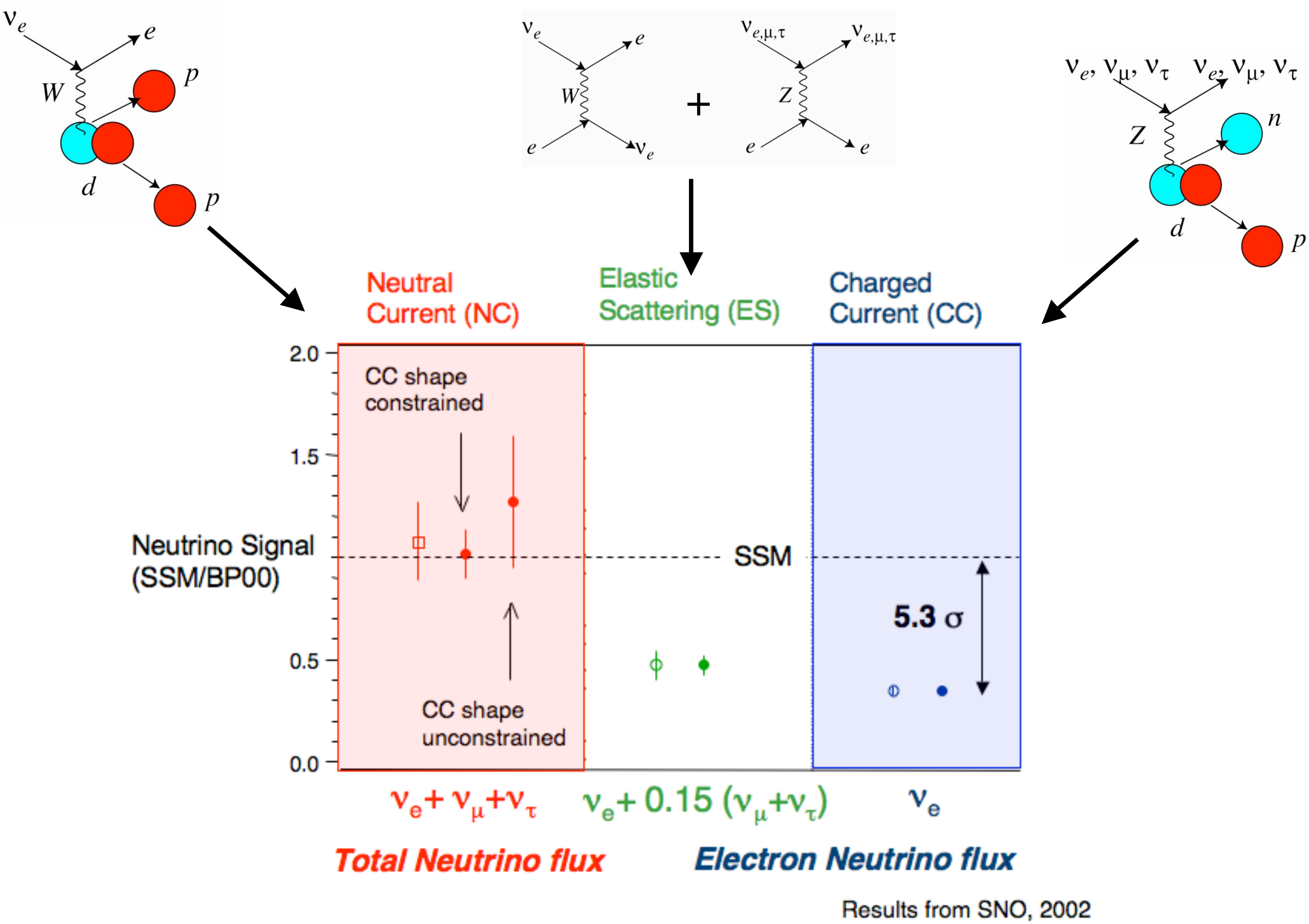
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

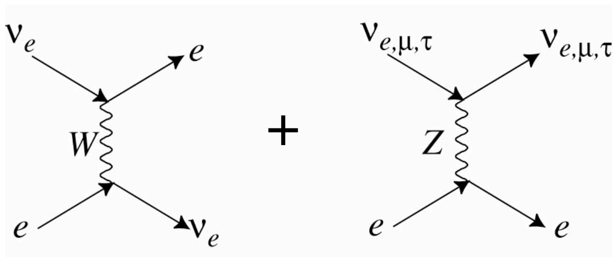


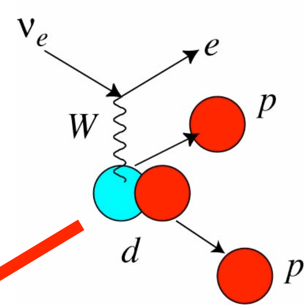


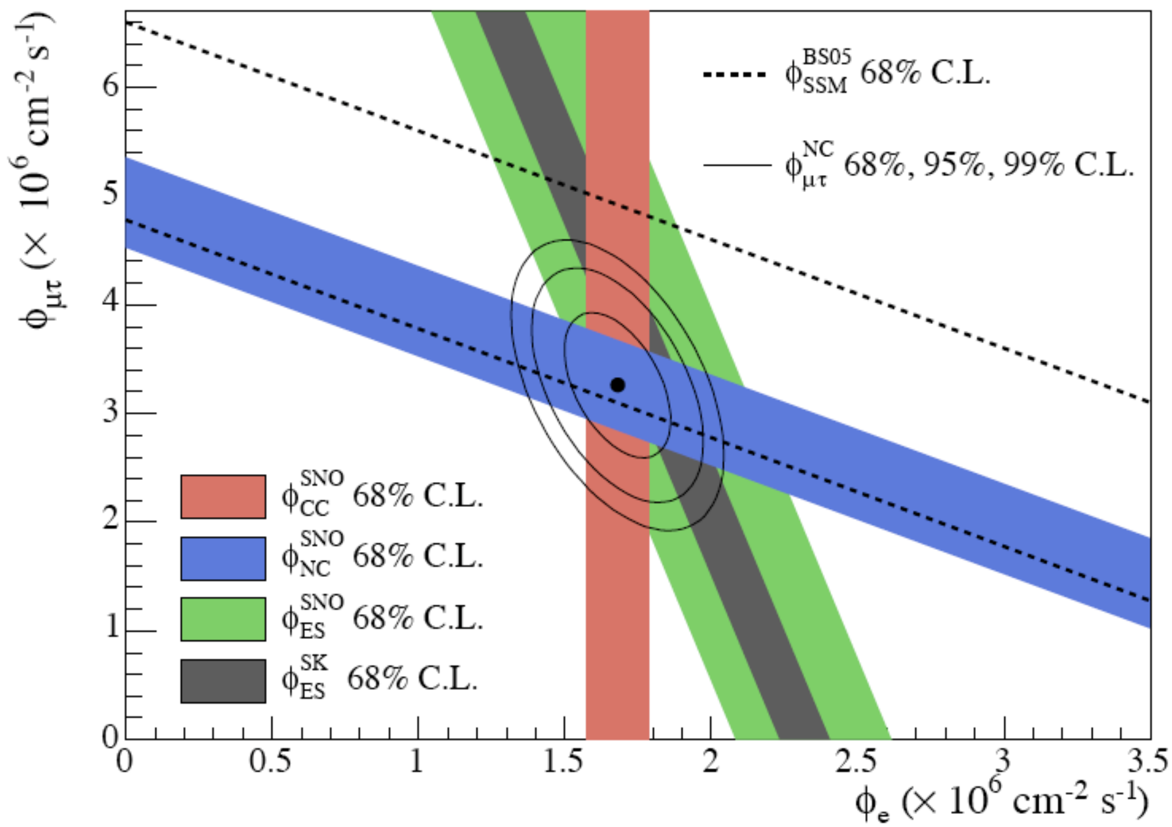


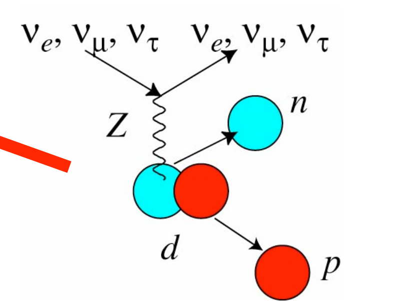
2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$

Recent results from SNO

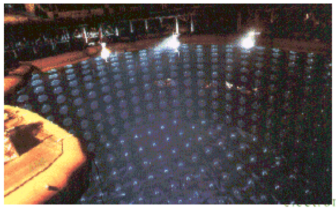


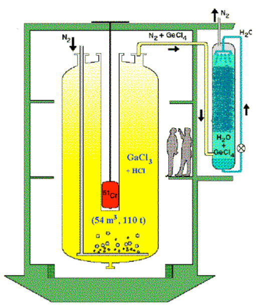


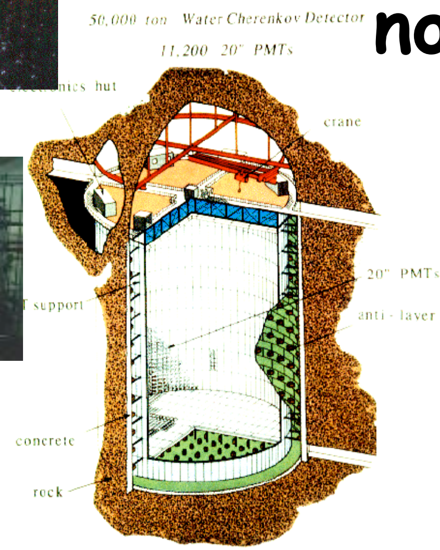


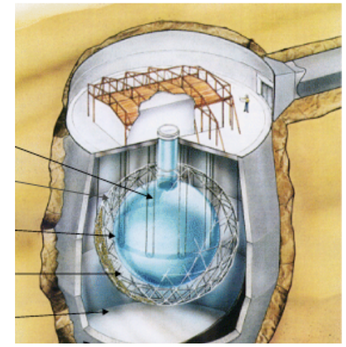


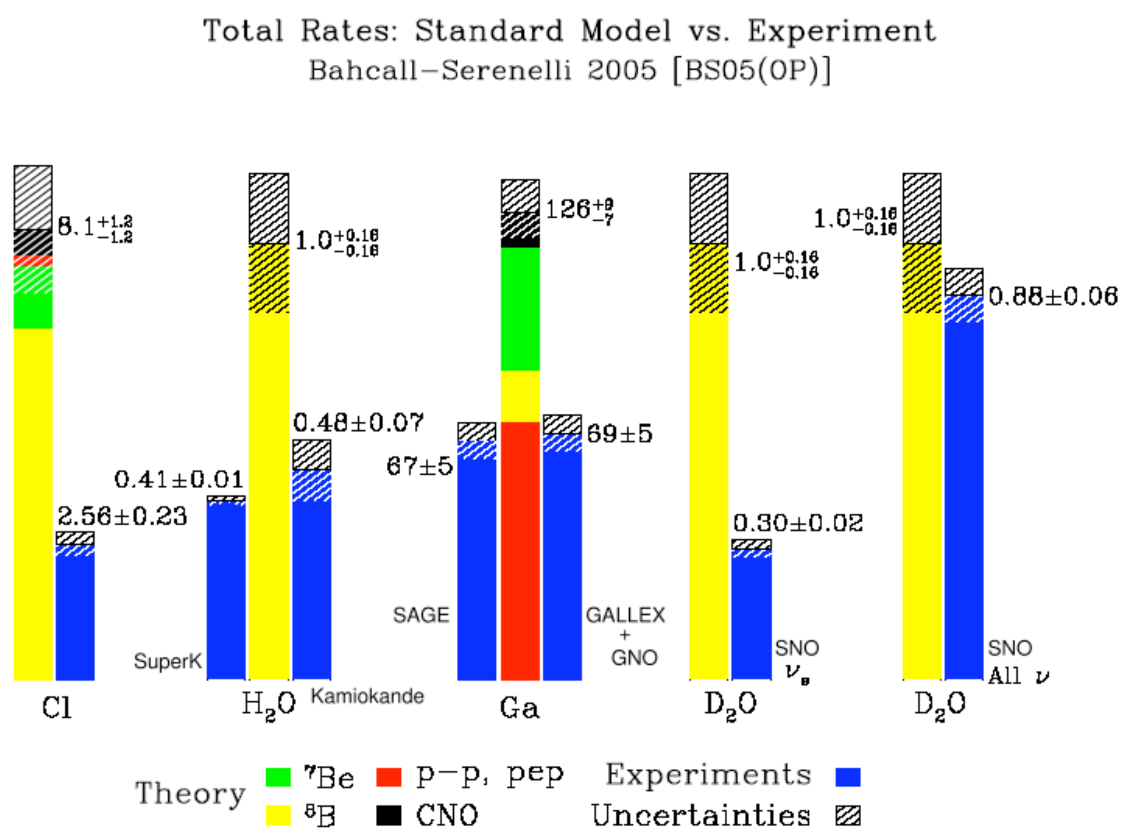
The "Solar Neutrino Problem": no longer a problem



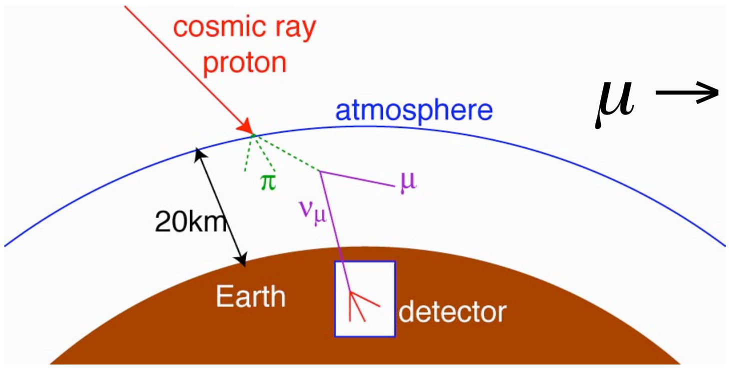








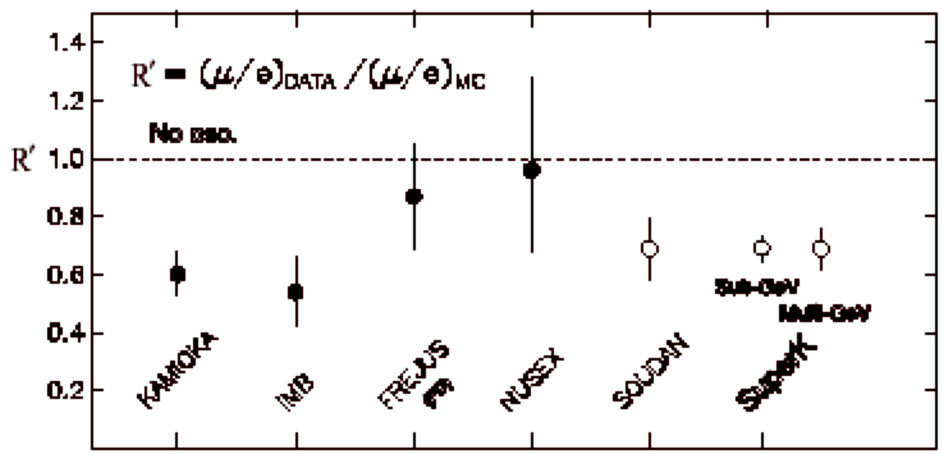
Atmospheric Neutrino Anomaly



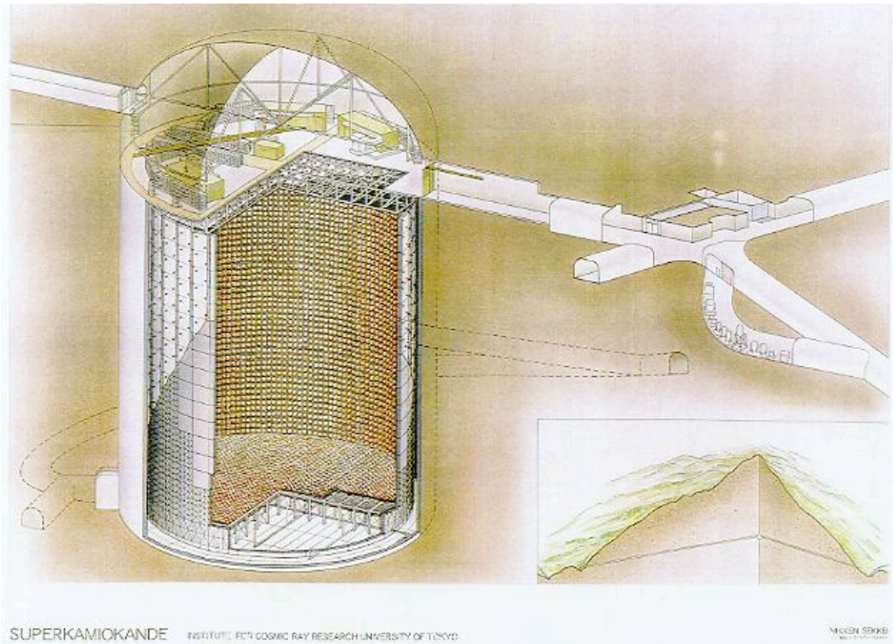
$$\pi \rightarrow \mu + \nu_\mu$$

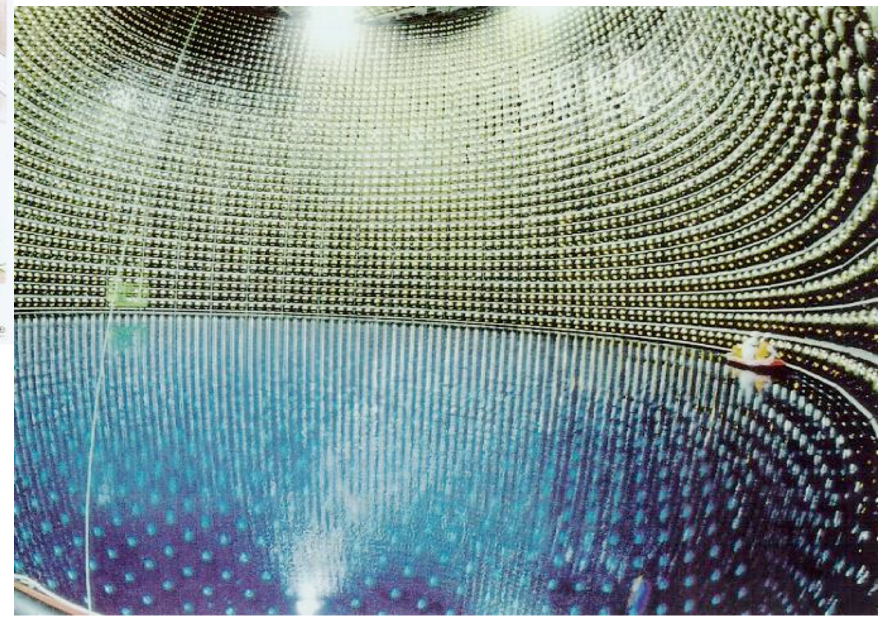
$$\mu \rightarrow e + \nu_e + \nu_\mu$$

$$\longrightarrow \quad N(\nu_\mu) = 2N(\nu_e)$$

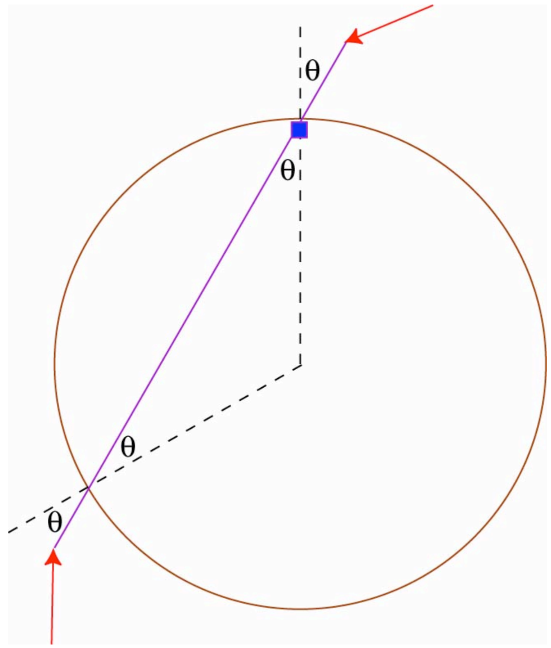


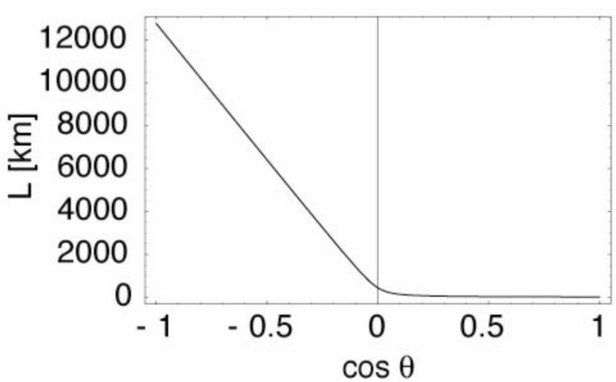
SuperKamiokaNDE detector

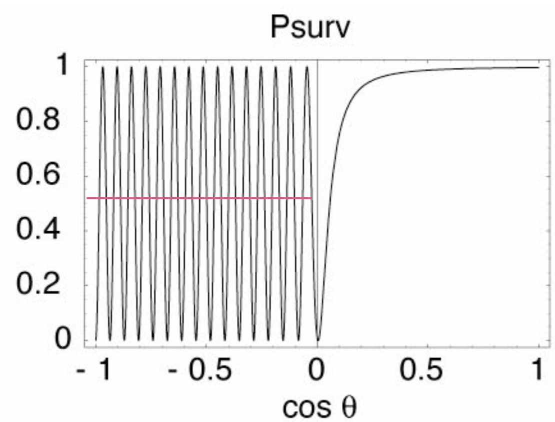




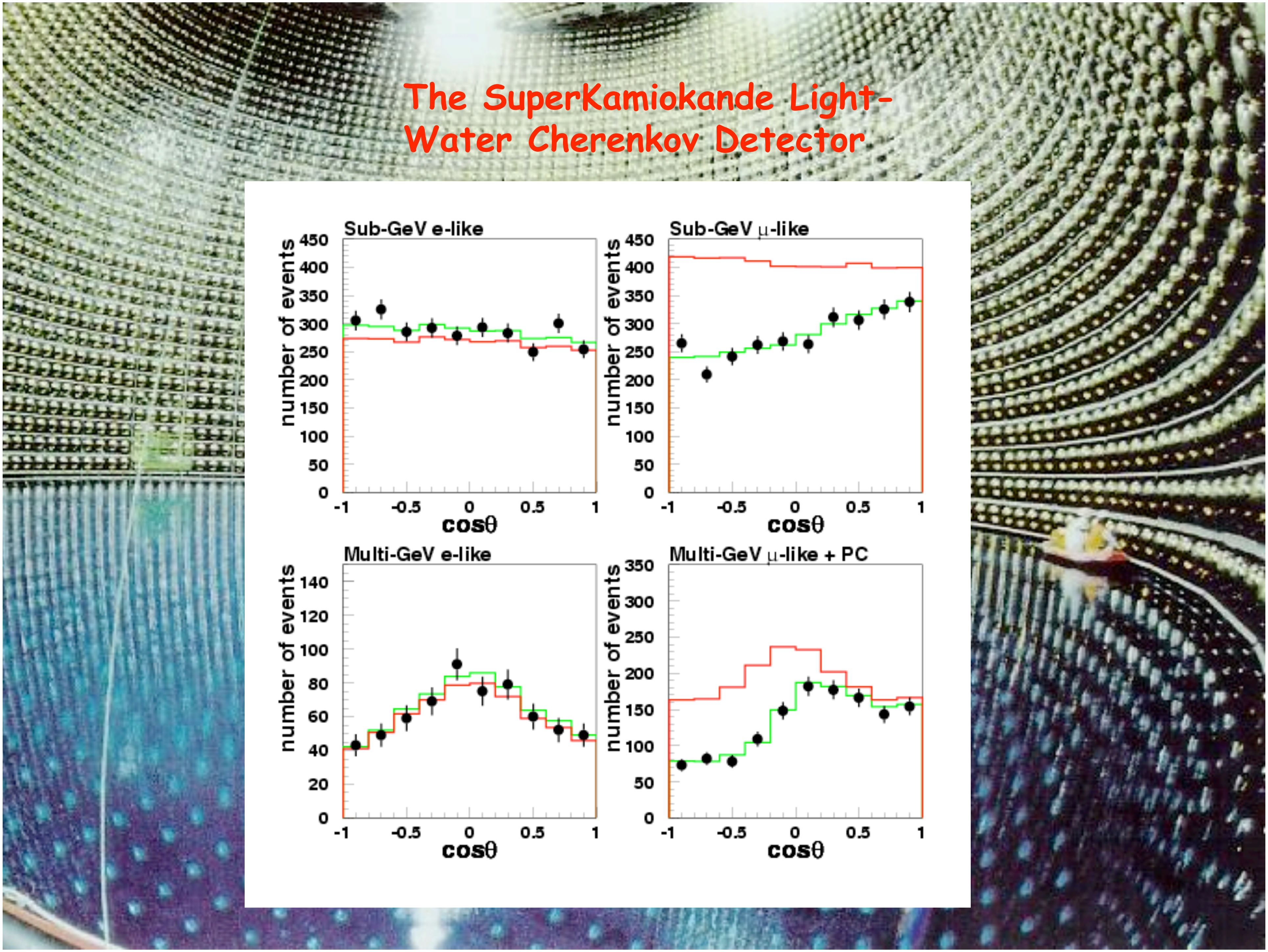
50,000 ton water Cherenkov detector


θ
θ
θ
θ


12000
10000
8000
6000
4000
2000
0
L [km]
- 1
- 0.5
0
0.5
1
cos θ

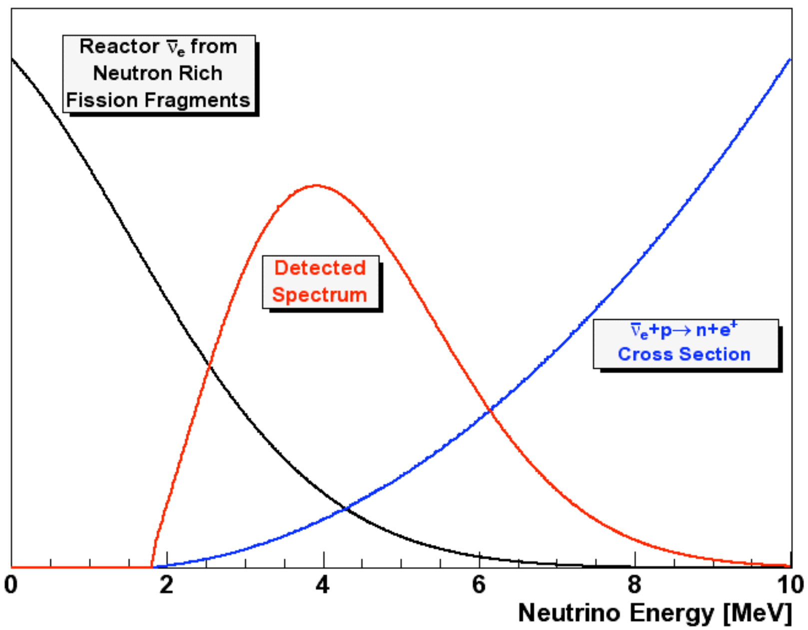

Psurv
1
0.8
0.6
0.4
0.2
0
- 1
- 0.5
0
0.5
1
cos θ

The SuperKamiokande Light-Water Cherenkov Detector

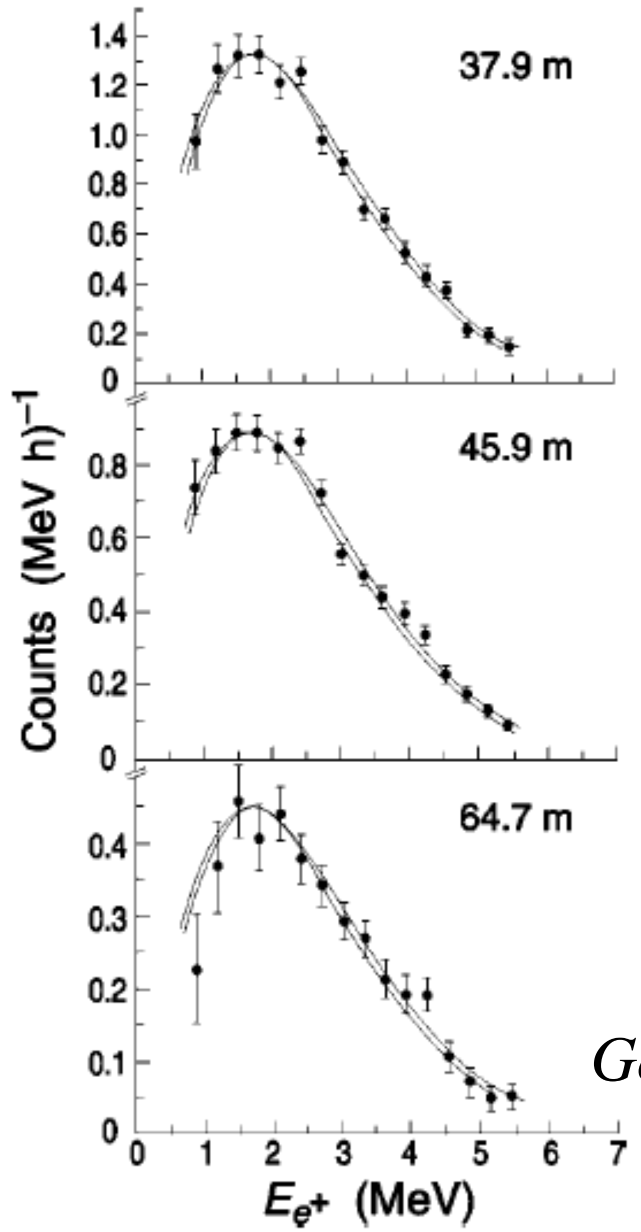


Reactor Neutrino Experiments

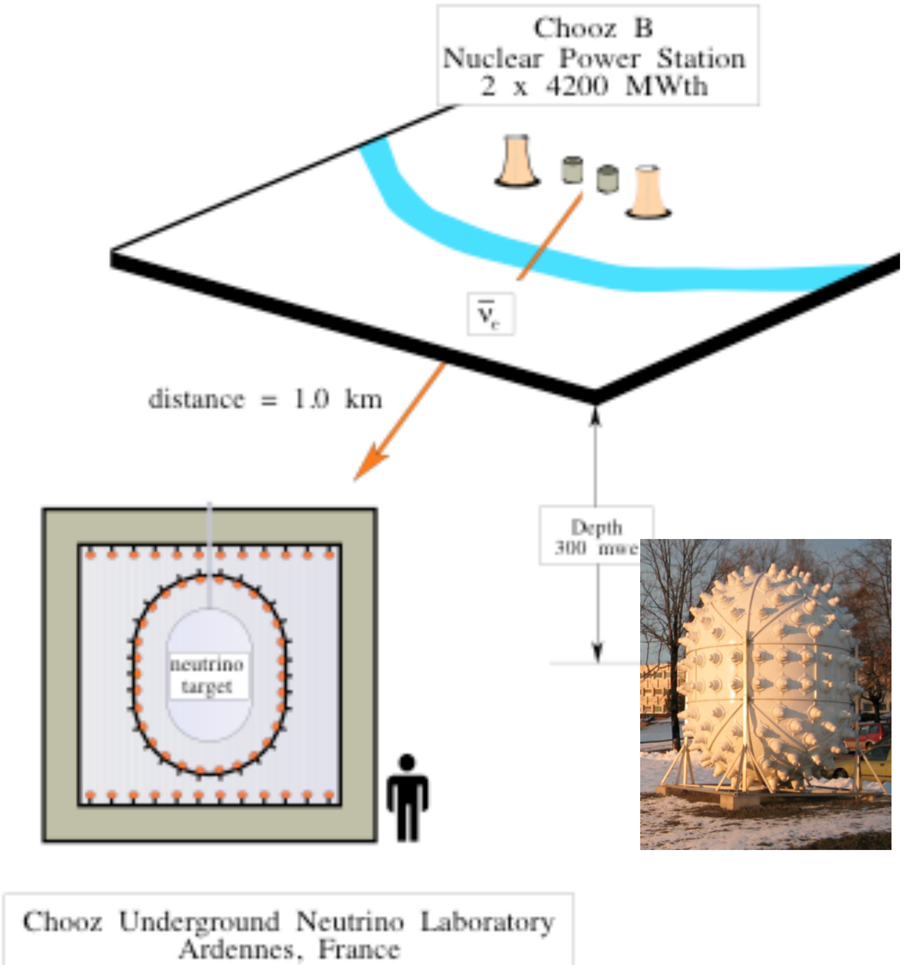
Neutrino Spectrum

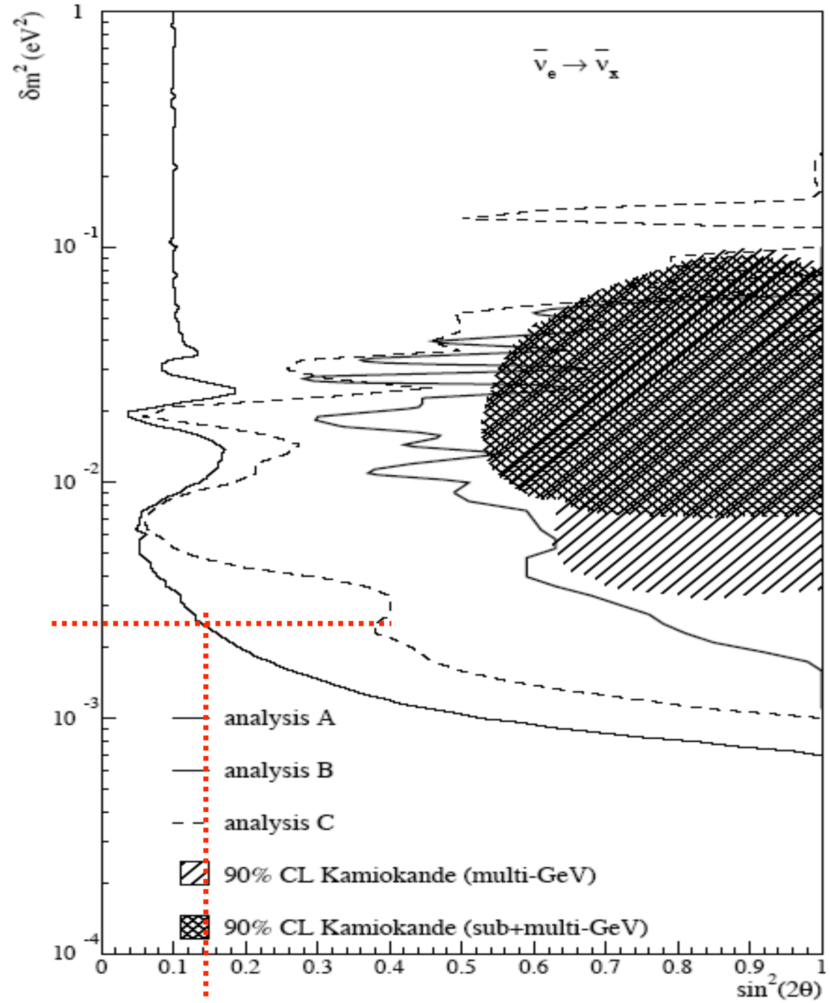


Positron Spectrum

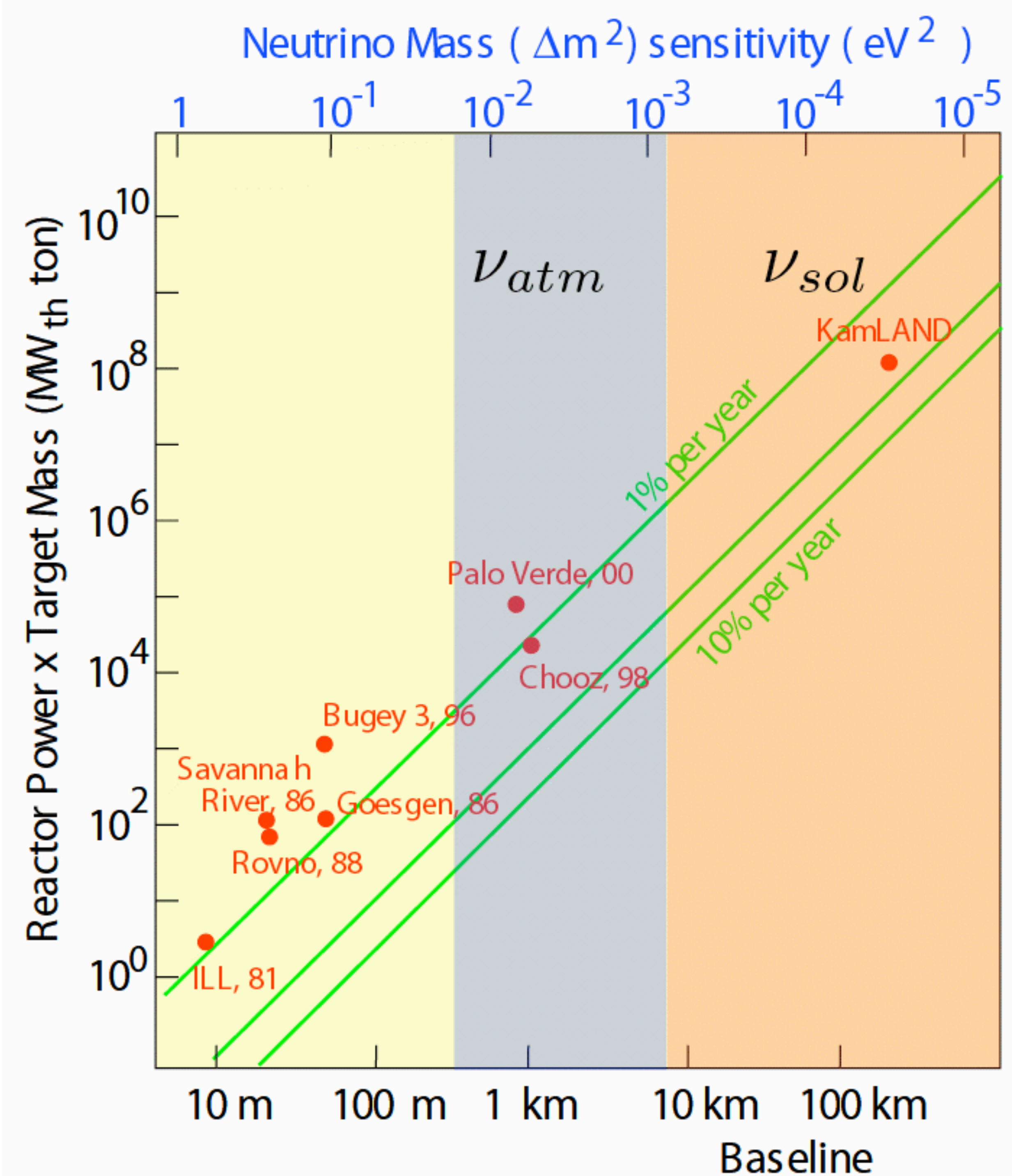


Goesgen





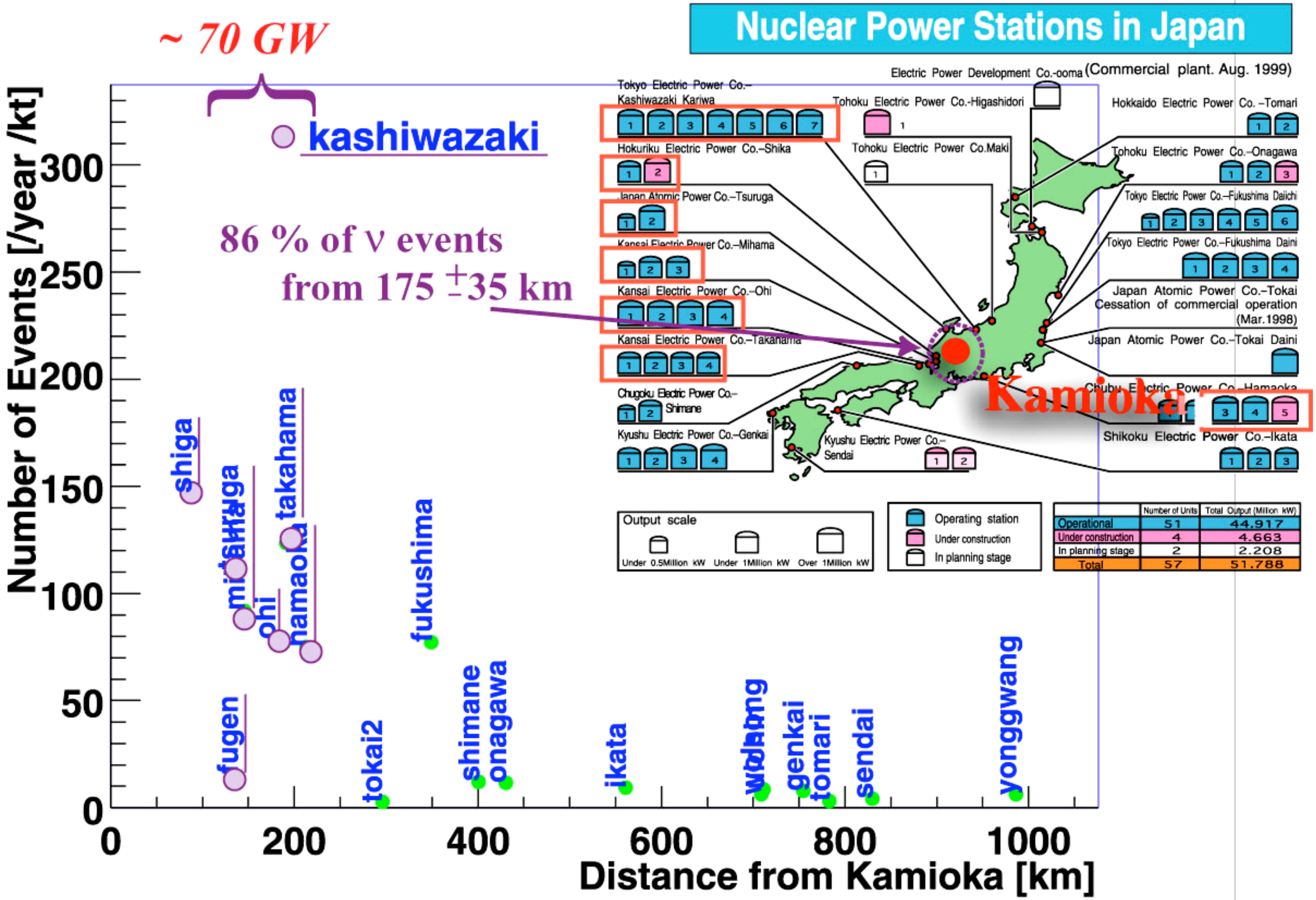
M. Appollonio, hep-ex/0301017

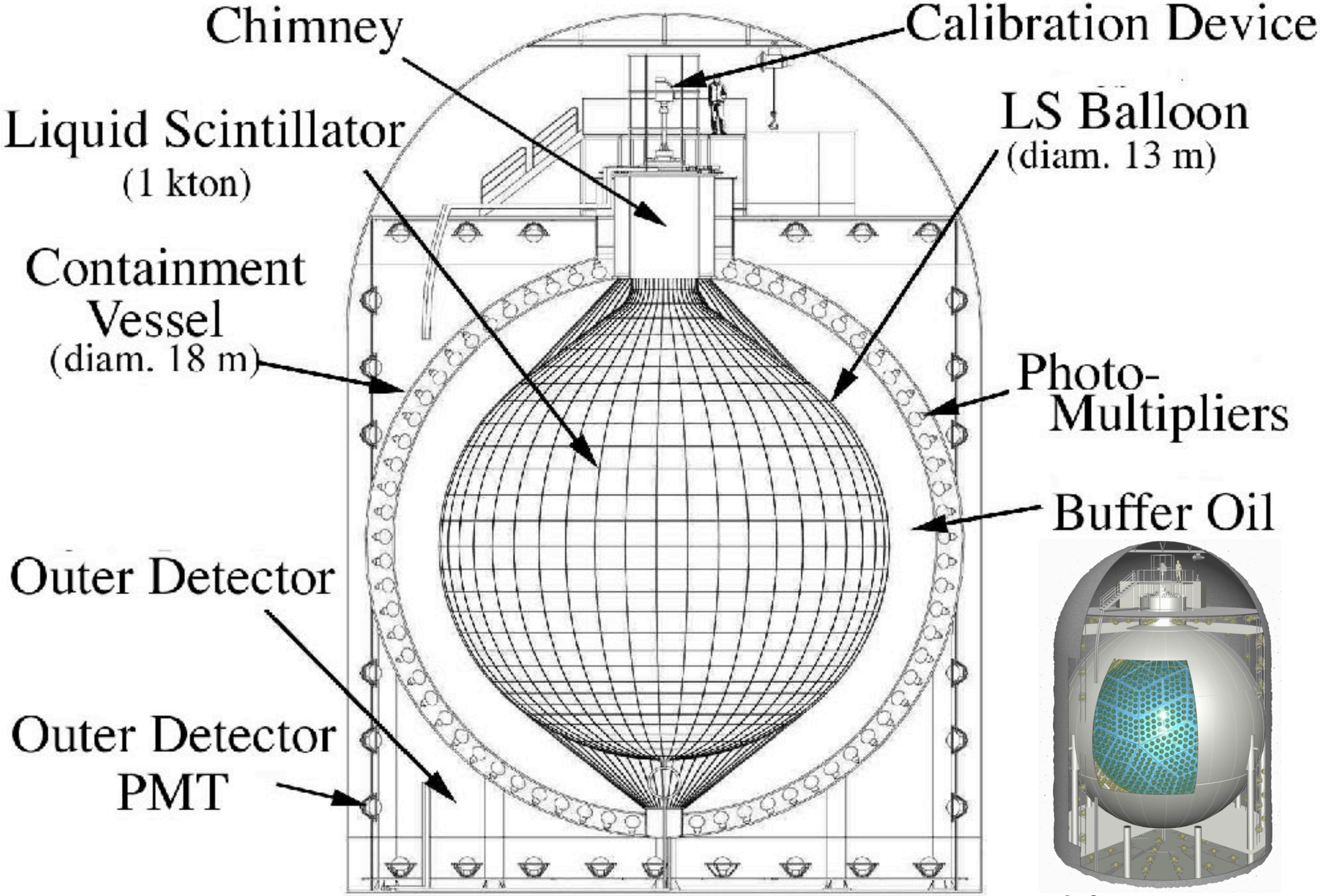


Neutrino Mass (Δm 2) sensitivity (eV 2)
1
10-1
10-2
10-3
10-4
10-5
Reactor Power x Target Mass (MWth ton)
1010
108
106
104
102
100
νatm
νsol
KamLAND
1% per year
10% per year
Palo Verde, 00
Chooz, 98
Bugey 3, 96
Savanna h
River, 86
Goesgen, 86
Rovno, 88
ILL, 81
10 m
100 m
1 km
10 km
100 km
Baseline

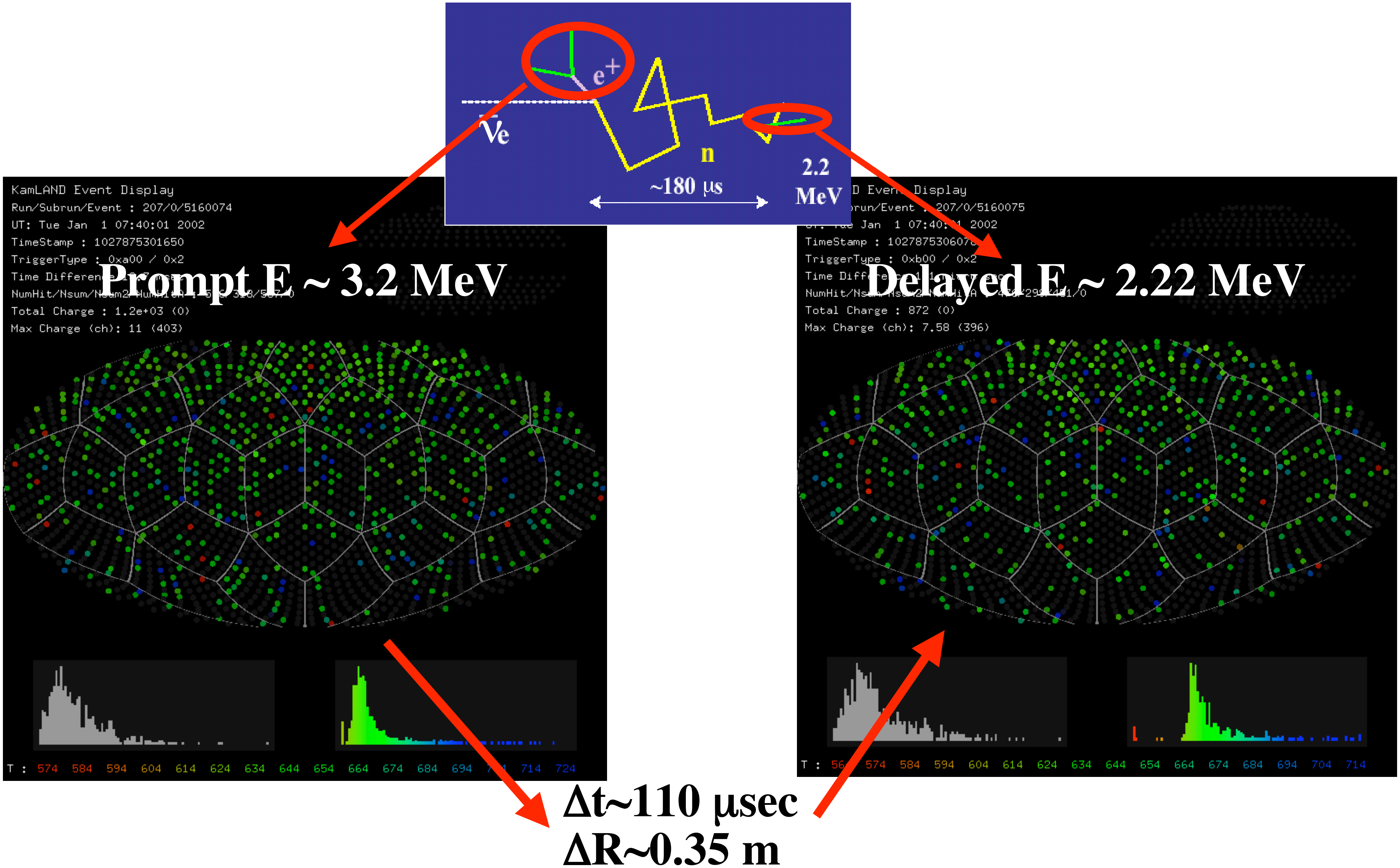
20 % of world nuclear power

~ 70 GW

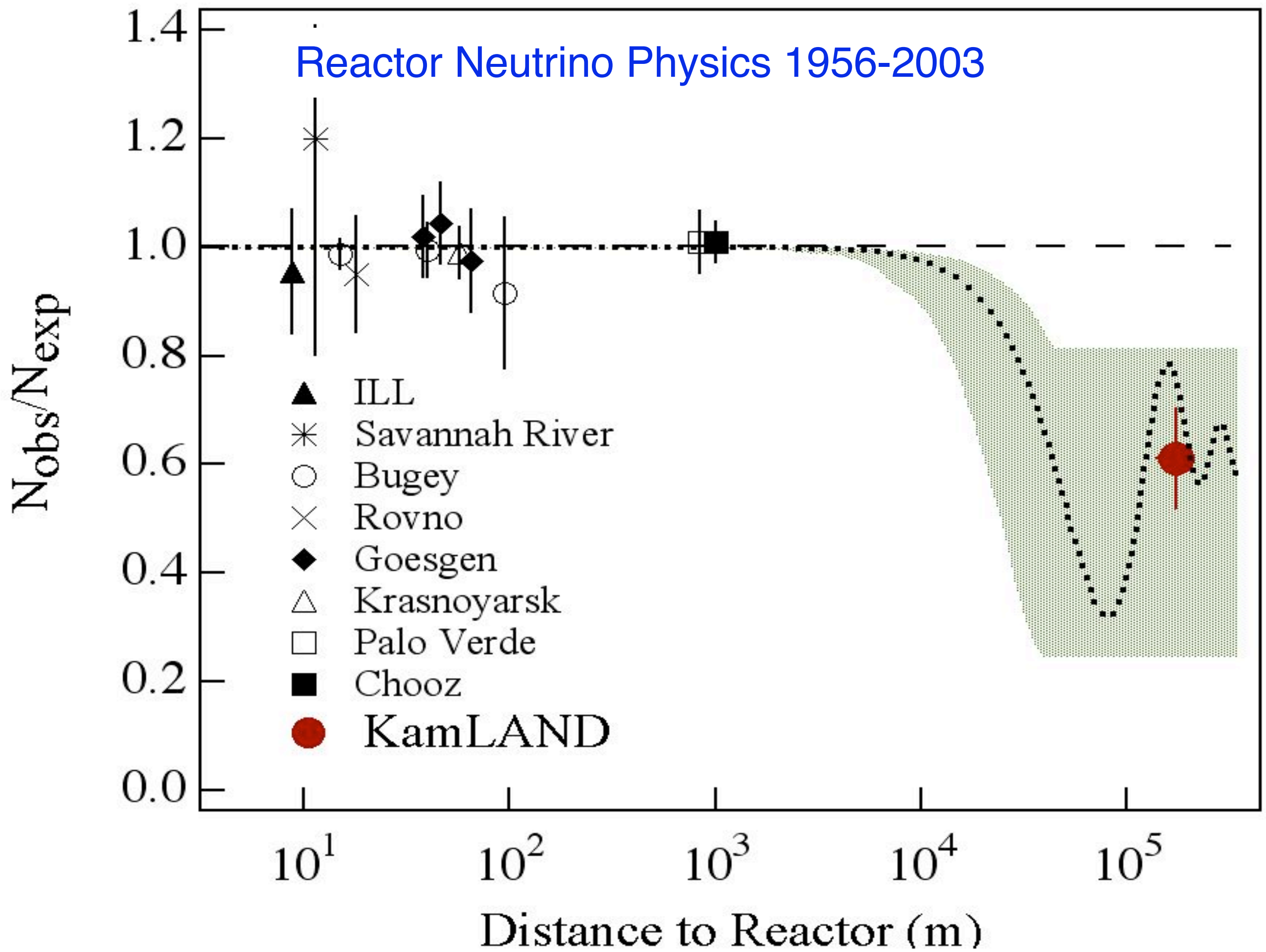




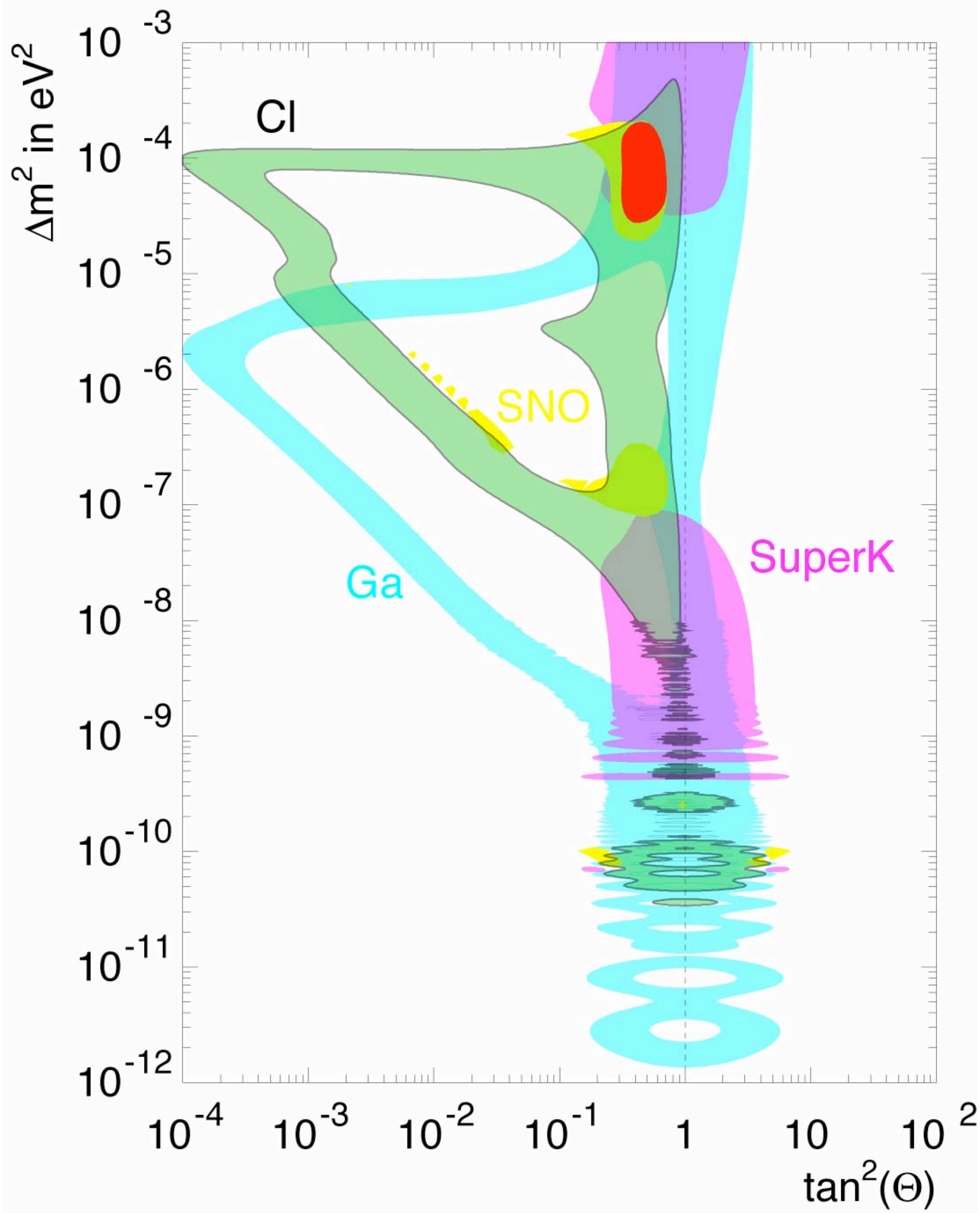
3.2 ton water veto



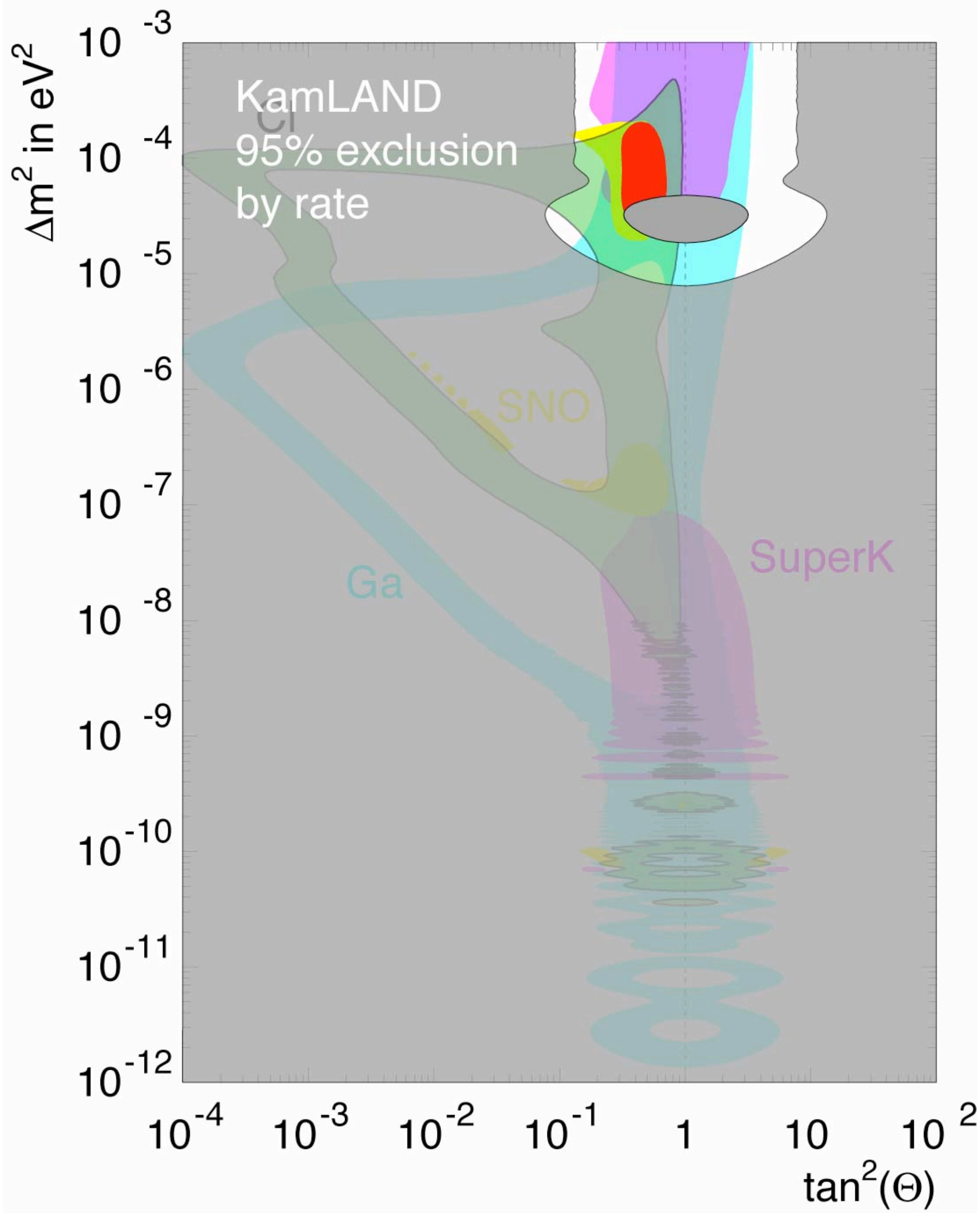
Candidate Neutrino Event



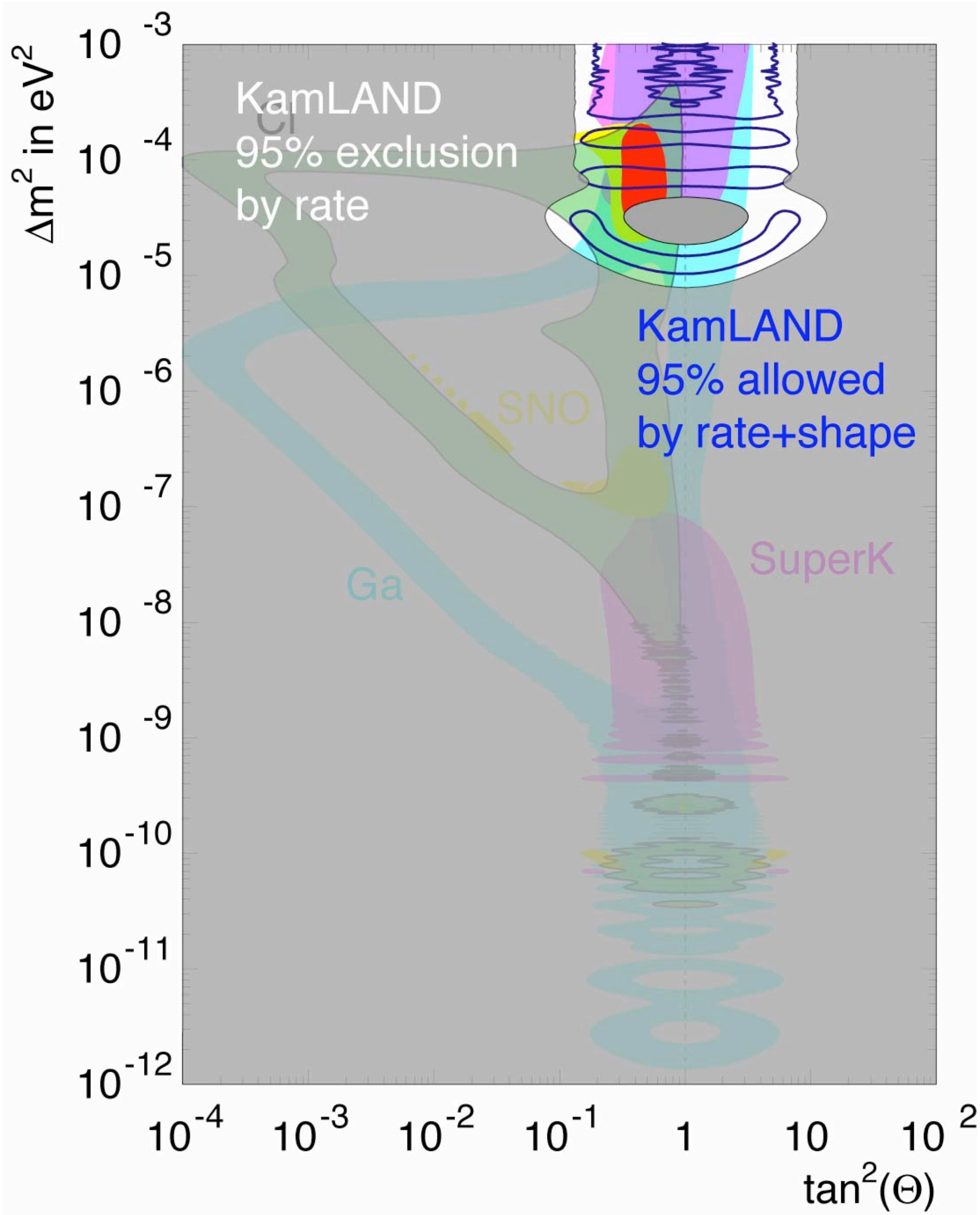
Reactor Neutrino Physics 1956-2003
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)



Δm² in eV²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
Cl
SNO
Ga
SuperK
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
10²
tan²(Θ)



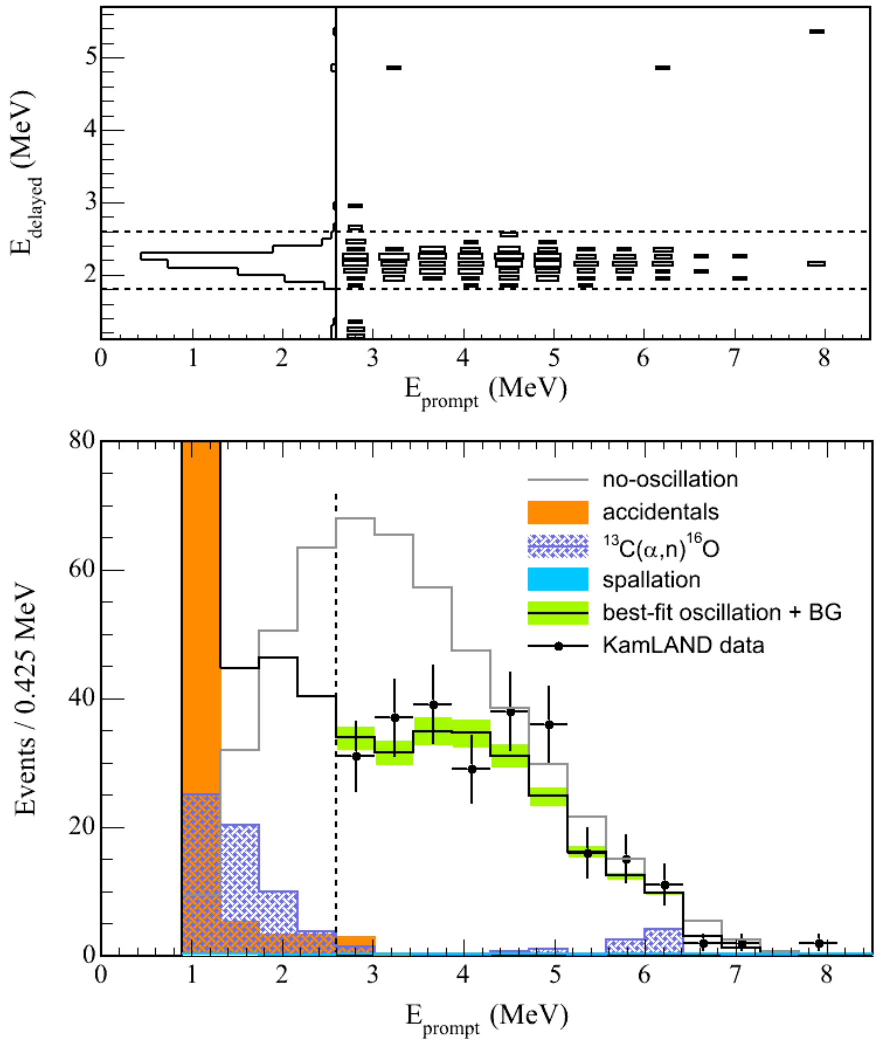
KamLAND
95% exclusion
by rate
Cl
SNO
SuperK
Ga
Δm^2 in eV^2
$\tan^2(\Theta)$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}



KamLAND
95% exclusion
by rate
Cl
KamLAND
95% allowed
by rate+shape
SNO
SuperK
Ga
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$

2004 Data Set

Is the Neutrino Spectrum Distorted?

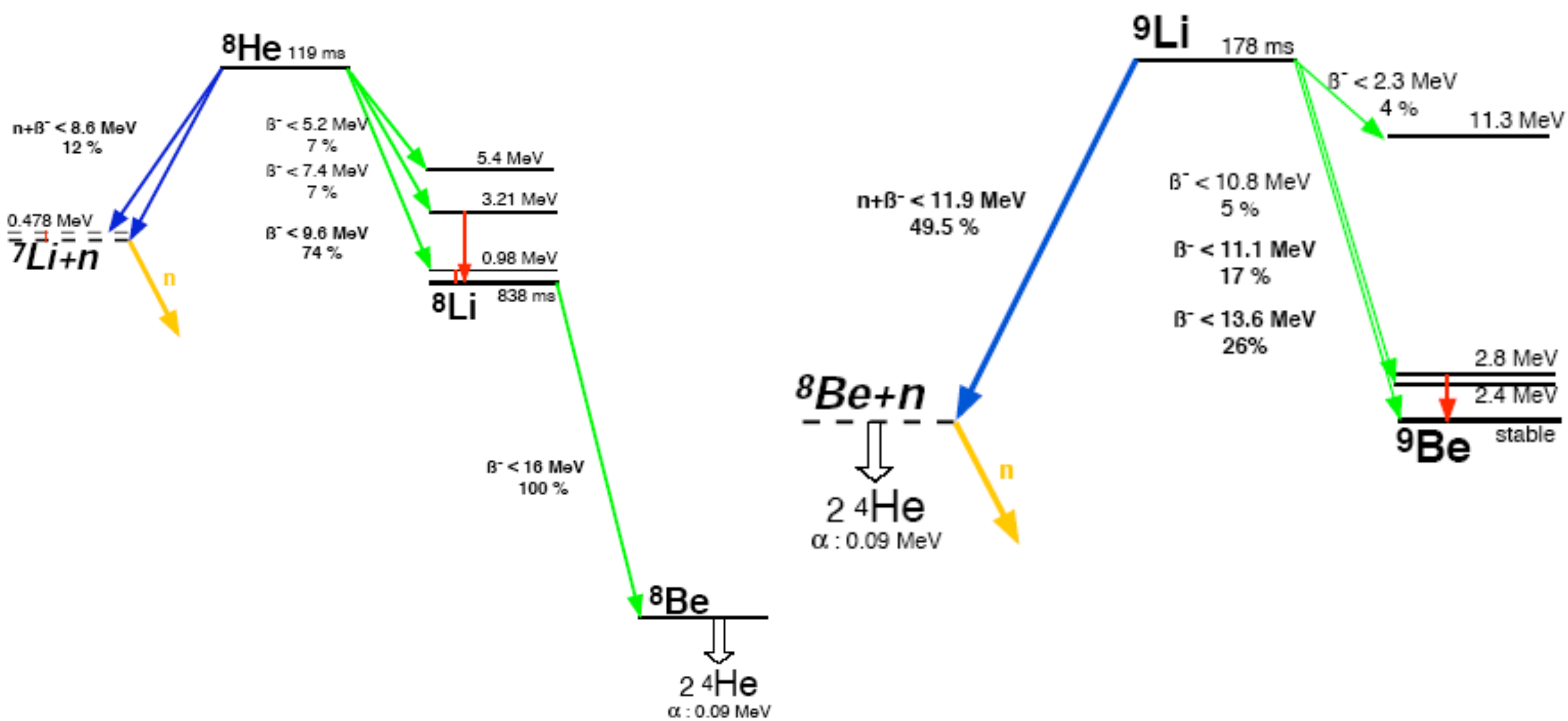


11.1% $\chi^2_p/DOF = 24.2/17$.

0.4% ($\chi^2_p/DOF = 37.3/18$).

$\chi^2_{/ 11\ d.o.f} = 13$

$^8He/^9Li$ Background

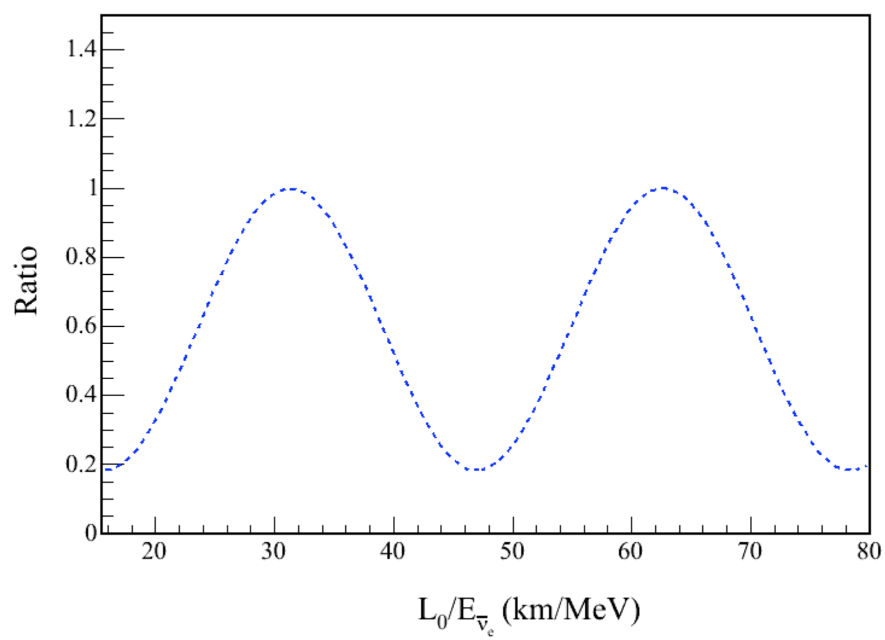


Looking for the oscillation effect

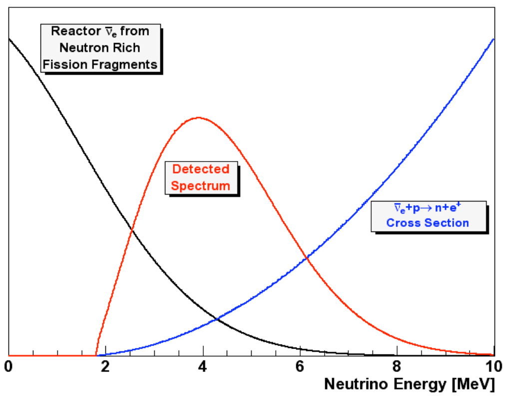
$$\left|\left\langle \psi_{\nu_e}(t) \middle| \psi_{\nu_e}(0) \right\rangle\right|^2 = 1 - \sin^2(2\theta)\sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar}t\right)$$

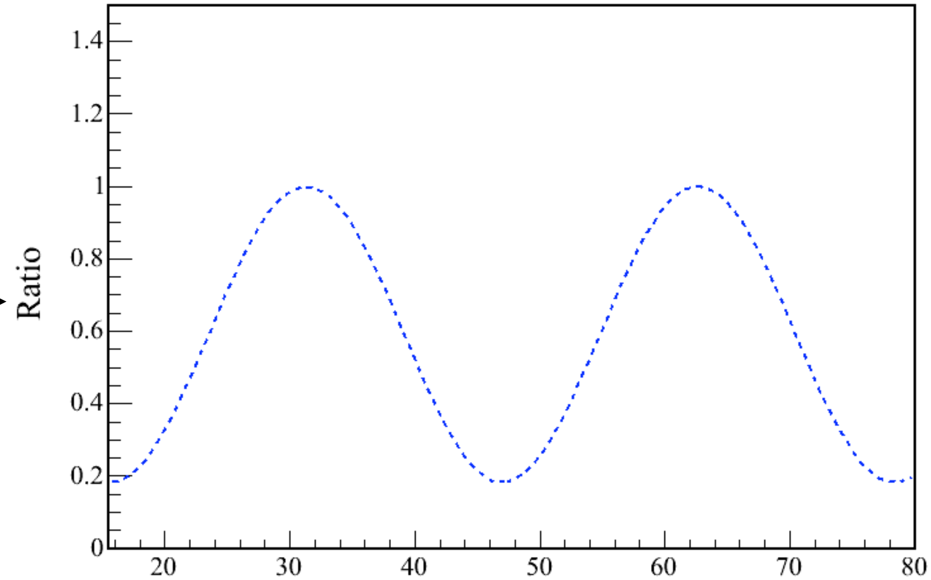
$$P_{ee}(L) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{(m_2^2 - m_1^2)L}{E}\right)$$

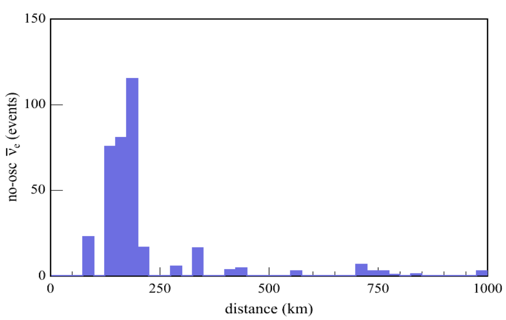
$$L = c \bullet t_{lab} \qquad t_{restframe} = \frac{t_{lab}}{\gamma} = \frac{m}{E} t_{lab}$$

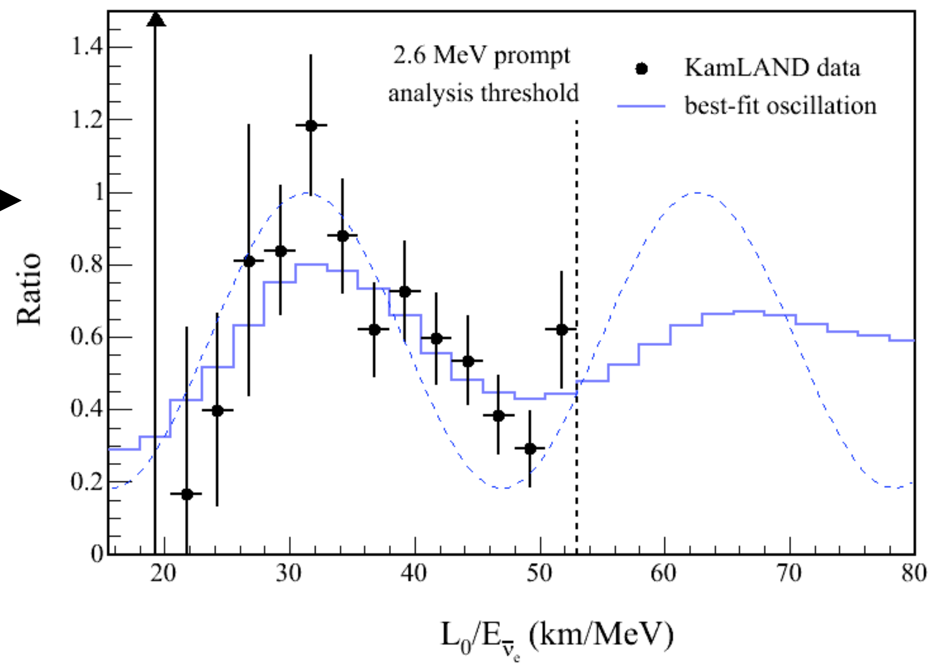


Observing the oscillations in the neutrino rest frame



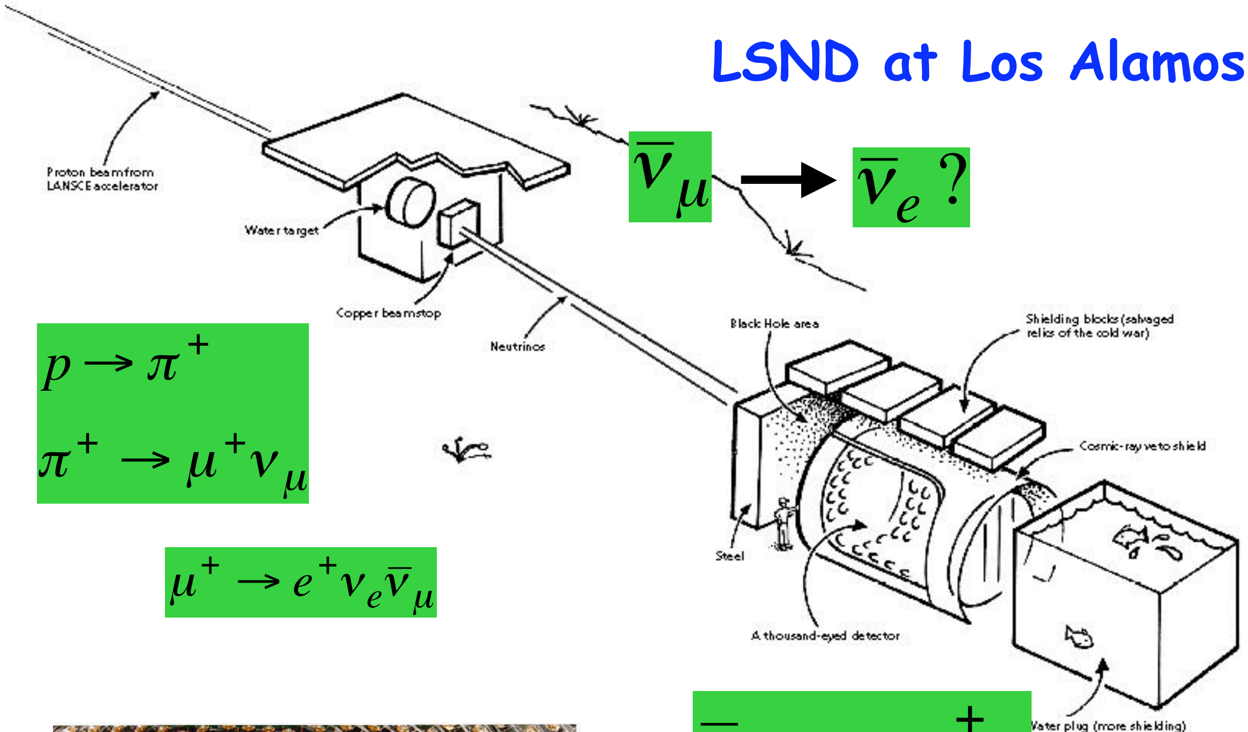






Do ‘sterile’ neutrinos exist?

LSND at Los Alamos



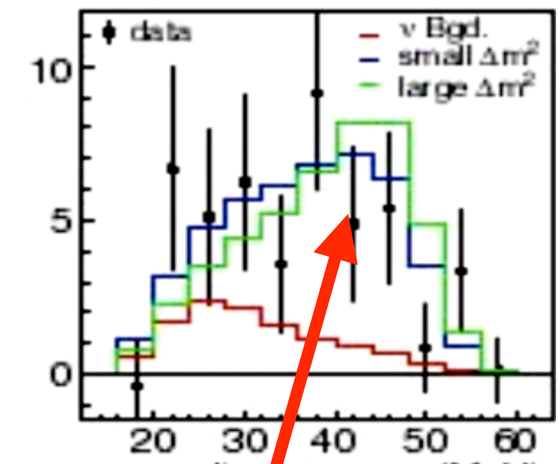
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

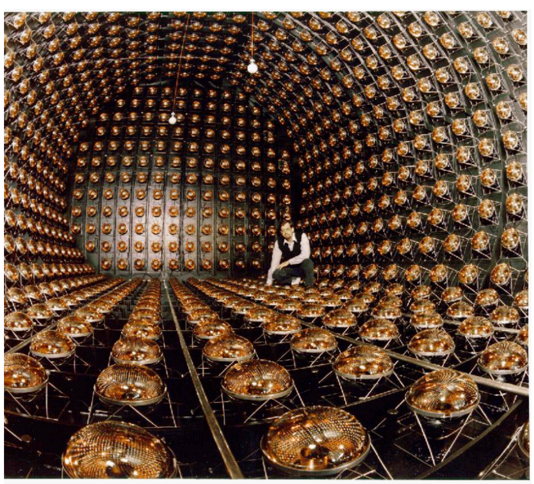
$p \rightarrow \pi^+$

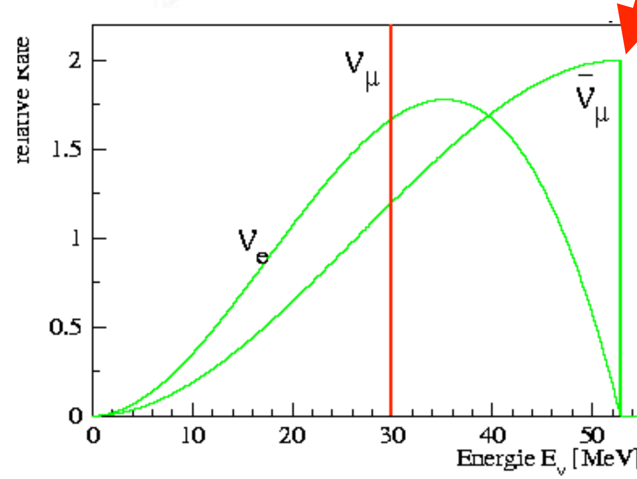
$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

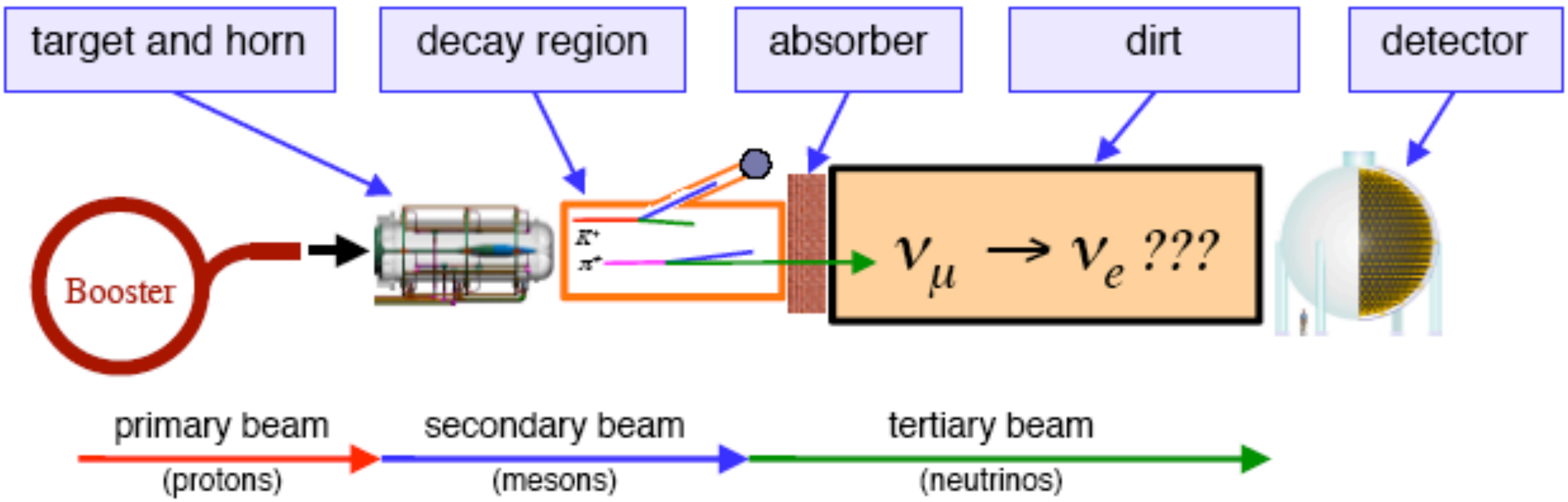
$\bar{\nu}_e p \rightarrow e^+ n$







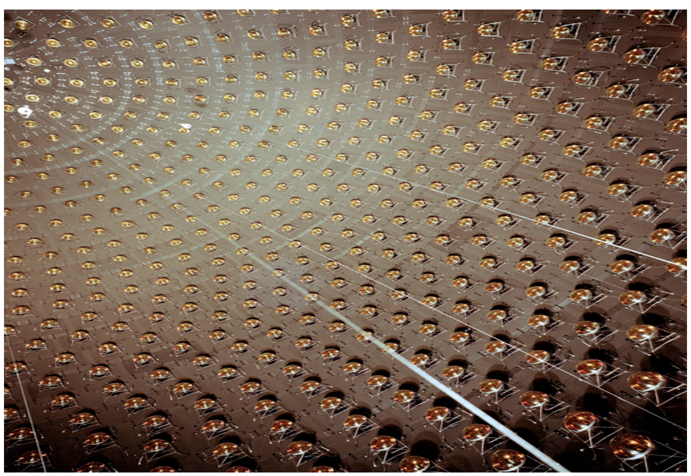
MiniBooNE



Order of magnitude higher energy (~500 MeV) than LSND (~30 MeV)

Order of magnitude longer baseline (~500 m) than LSND (~30 m)

Experiment capable of confirming LSND



- MiniBooNE

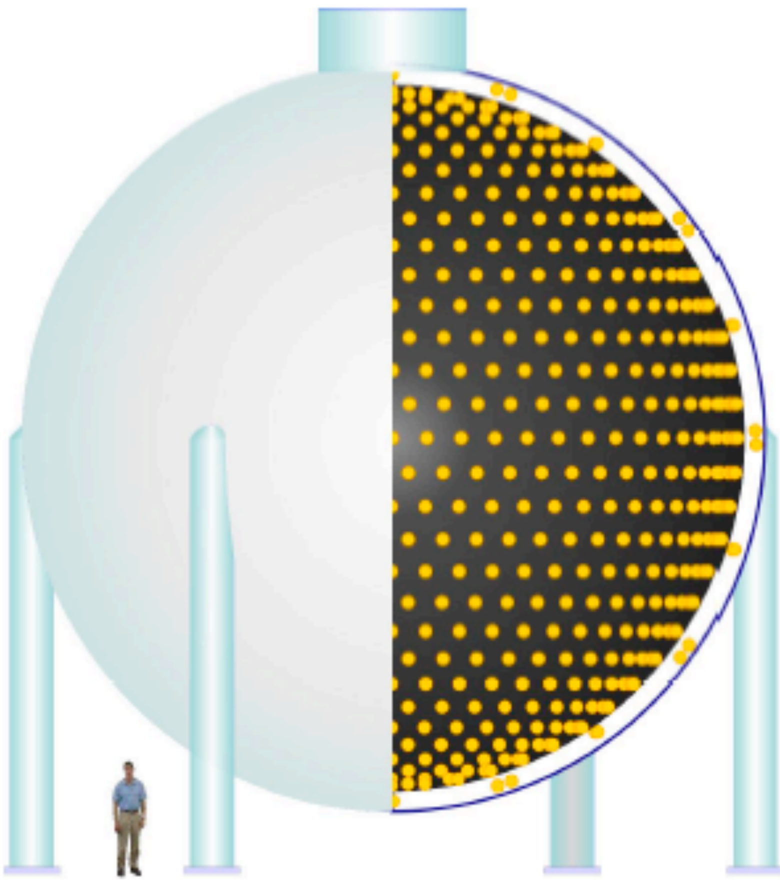
  - 1 GeV neutrinos (Booster)

  - 800 ton oil cerenkov

  - Operating since 2003

  - $\nu_\mu \rightarrow \nu_e$ appearance

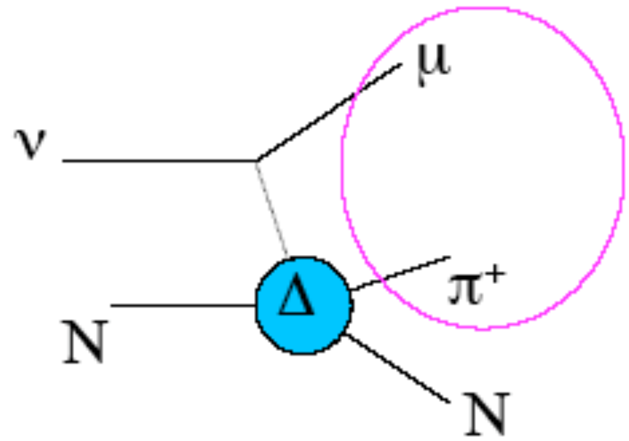
The MiniBooNE Detector



- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere
  (10 meter “fiducial” volume)
  - Filled with 800 t
    of pure mineral oil (CH_2)
    (Fiducial volume: 450 t)
  - 1280 inner phototubes,
    240 veto phototubes
  - Simulated with a GEANT3 Monte Carlo

Events producing pions

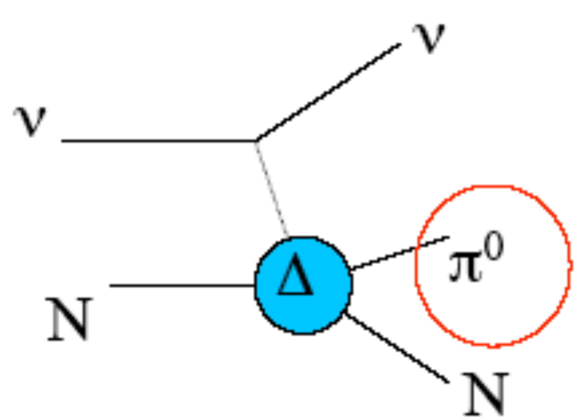
25%



$CC\pi^+$

Easy to tag due to 3 subevents. Not a substantial background to the oscillation analysis.

8%



$NC\pi^0$

The π^0 decays to 2 photons, which can look "electron-like" mimicking the signal...

(also decays to a single photon with 0.56% probability)

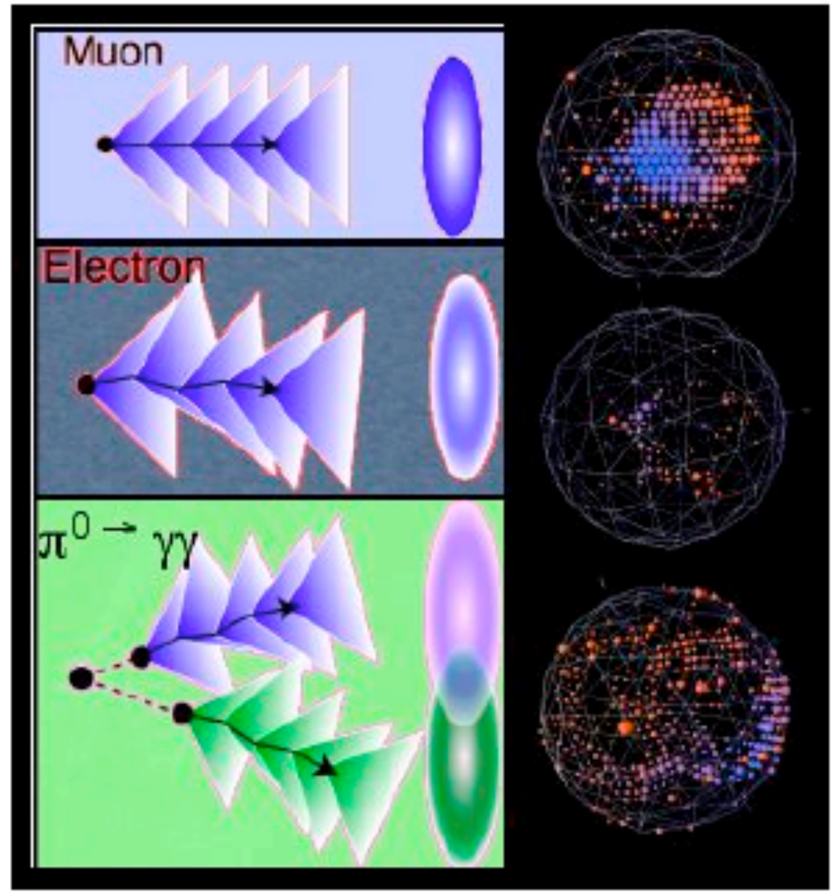
<1% of π^0 contribute to background.

The types of particles these events produce:

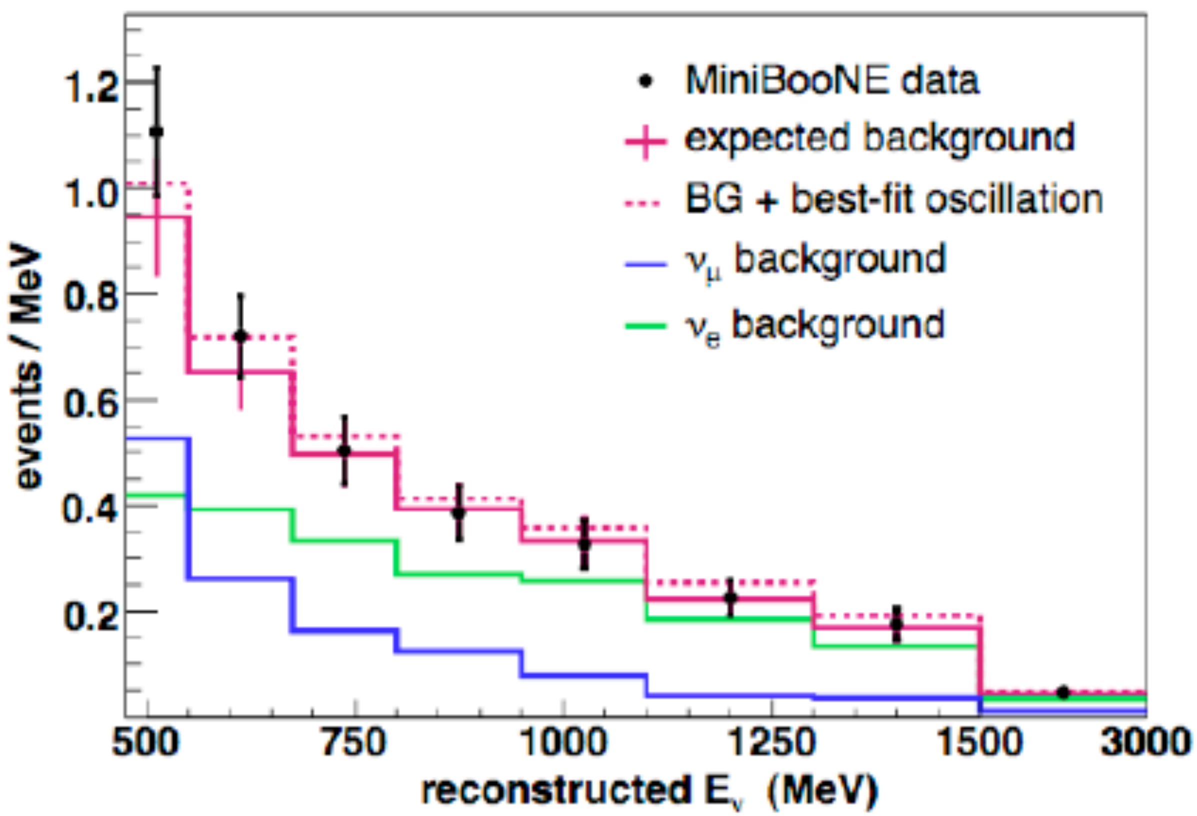
Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

π^0s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.



Track Based energy dependent fit results:
Data are in good agreement with background prediction.

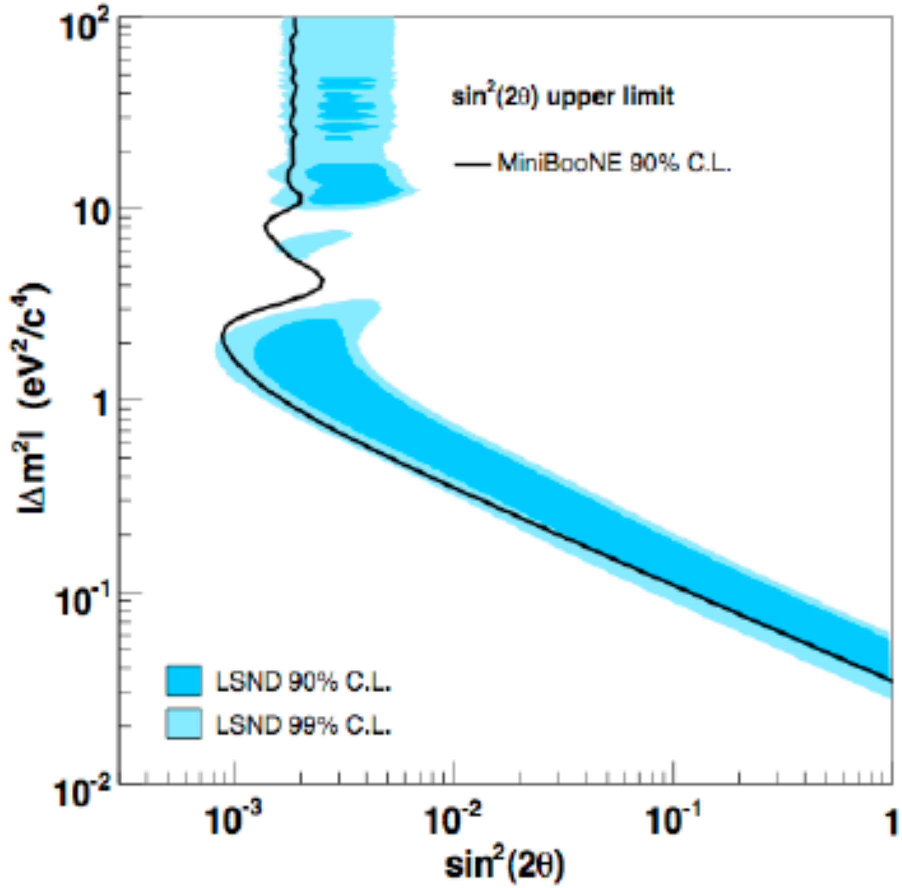


Error bars are diagnonals of error matrix.

Fit errors for >475 MeV:
Normalization 9.6%
Energy scale: 2.3%

Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ eV^2)$

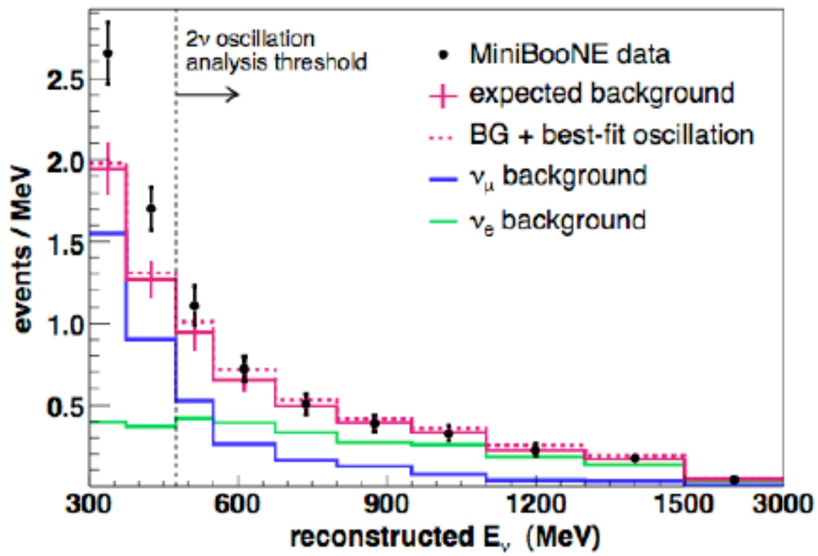
The result of
the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis
is a limit on oscillations:



χ^2 probability,
null hypothesis: 93%

Energy fit: $475 < E_\nu^{QE} < 3000$ MeV

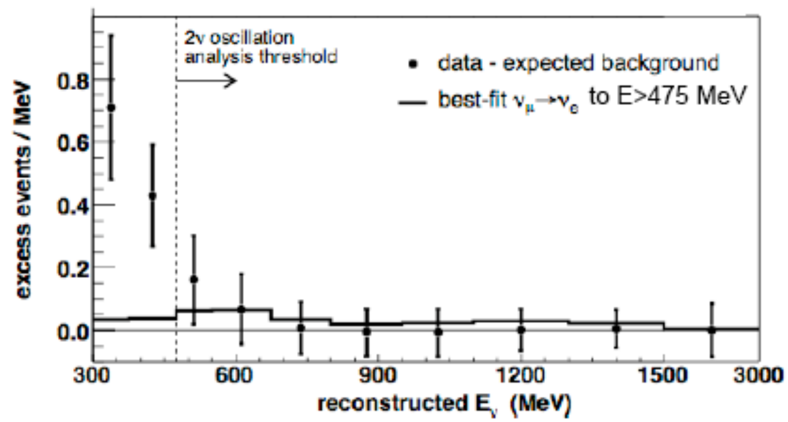
As planned before opening the box....
Report the full range:
$300<E_\nu^{QE}<3000$ MeV

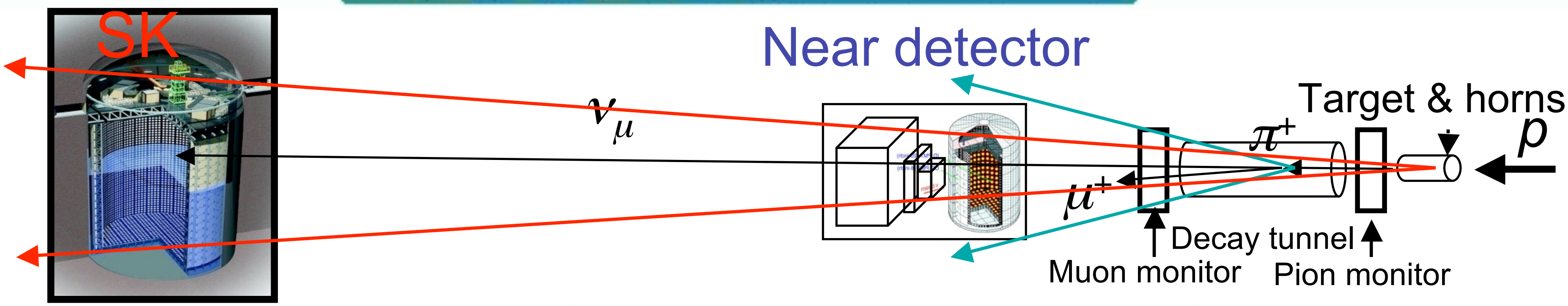


$96 \pm 17 \pm 20$ events above background, for $300<E_\nu^{QE}<475$MeV

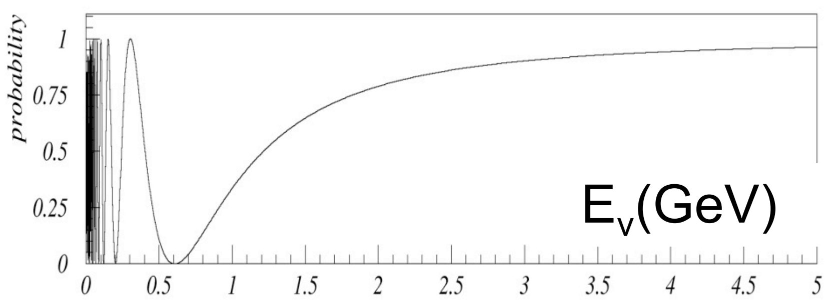
Deviation: 3.7σ

Background-subtracted:





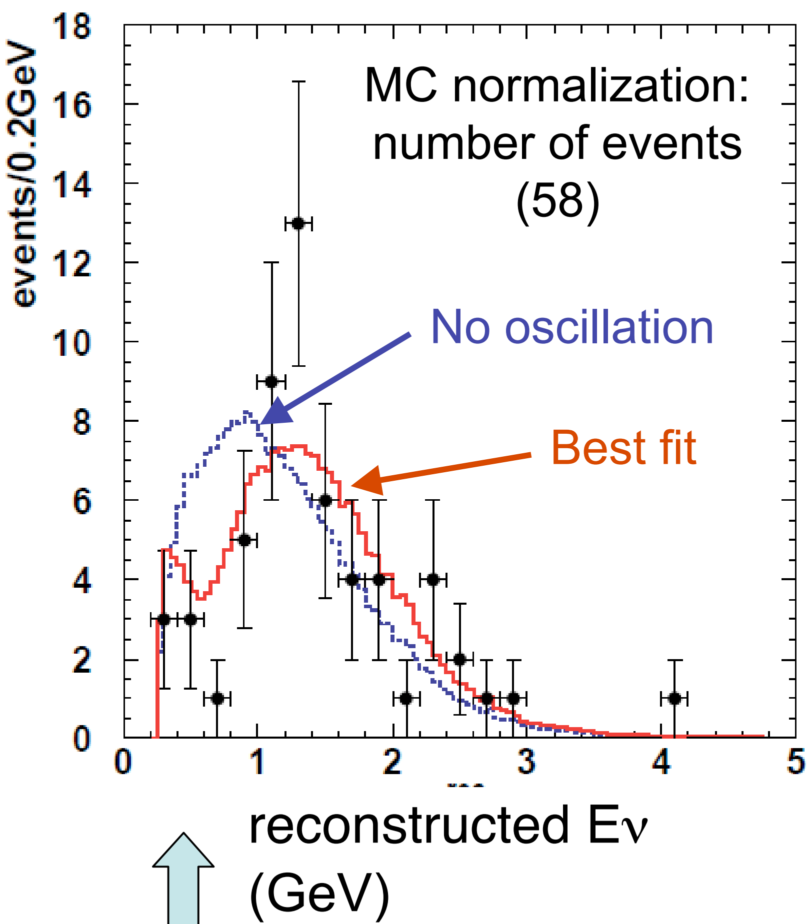
Neutrino oscillation probability for $\Delta m^2=0.003 eV^2$ and at 250km.



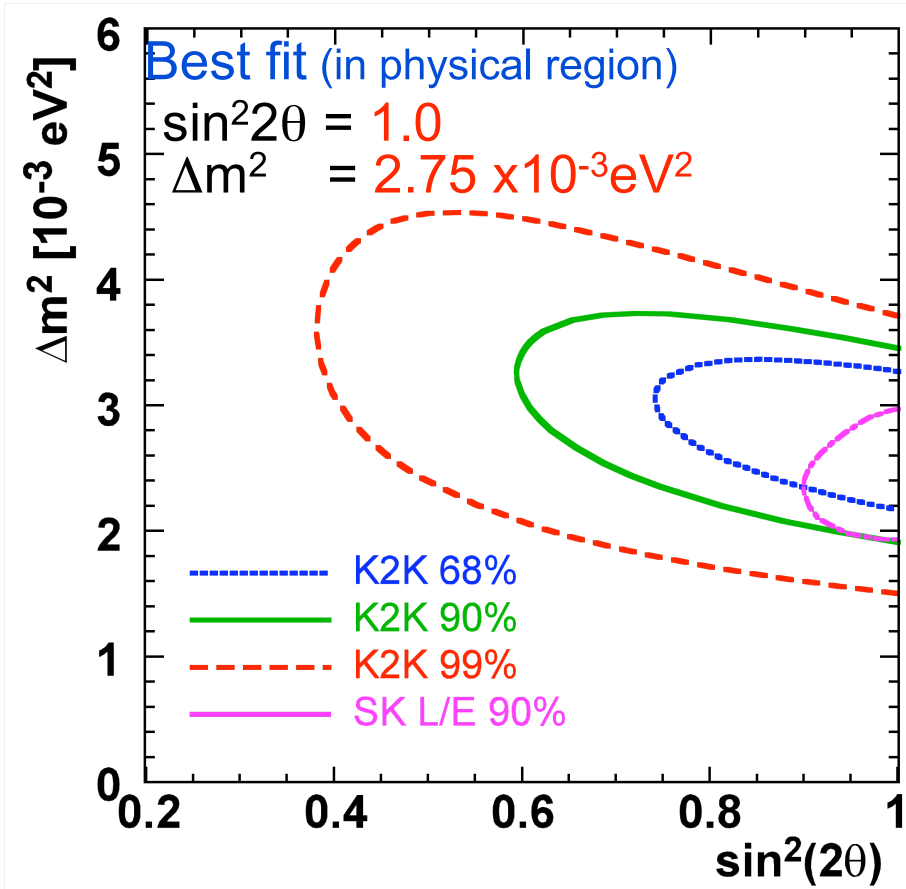
Study of $\nu_\mu \rightarrow \nu_\tau$ oscillation in K2K

Hep-ex/0606032

Based on **Number of events** + **Spectrum shape**

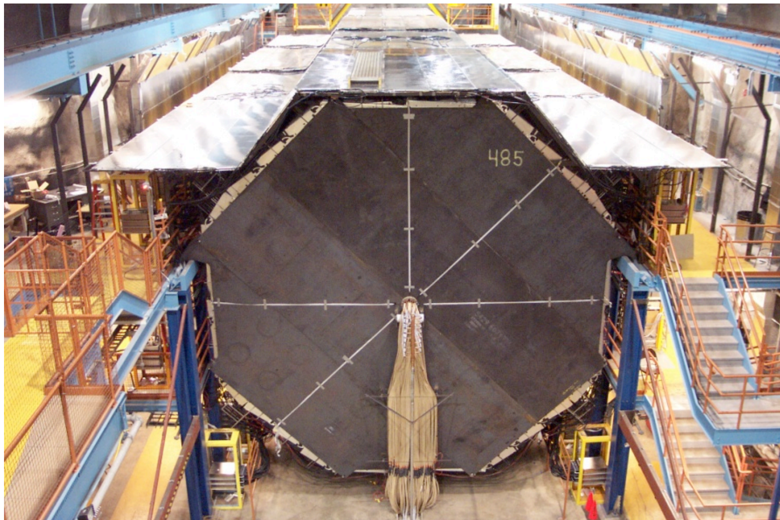


Deficit of events



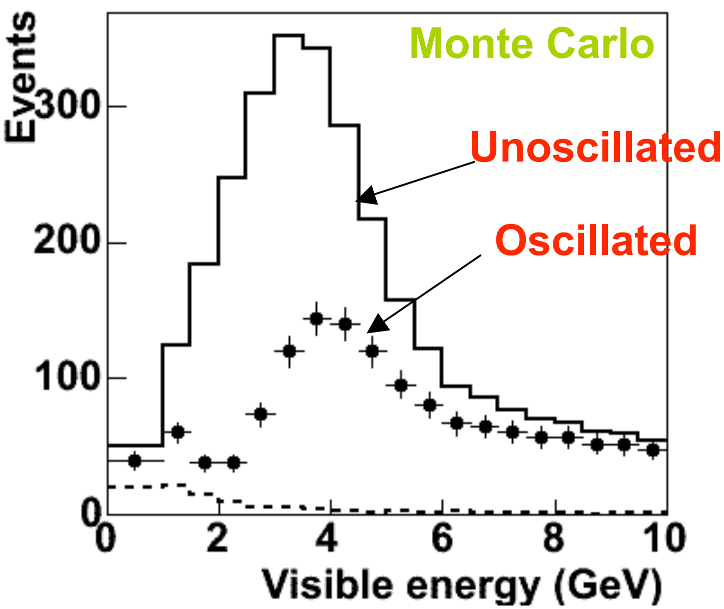
Consistent with the SK atmospheric neutrino result.

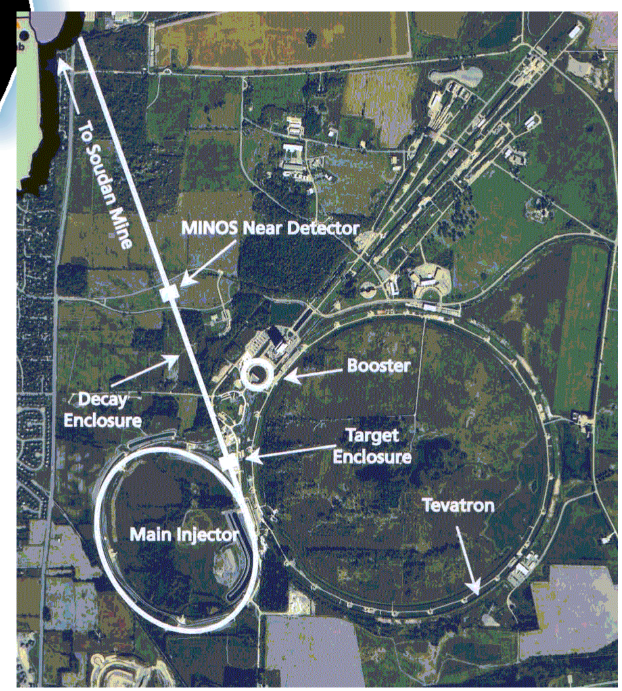
MINOS experiment at Fermilab



5.4 kton MINOS far detector

1 kton near detector

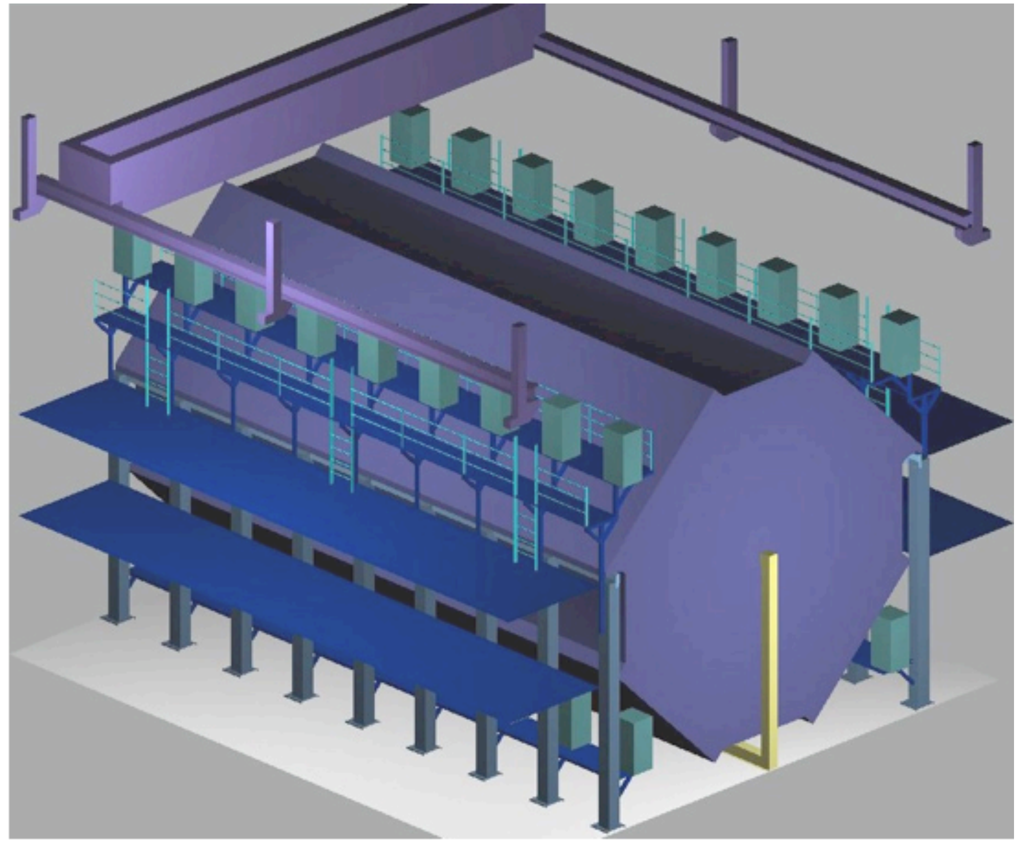




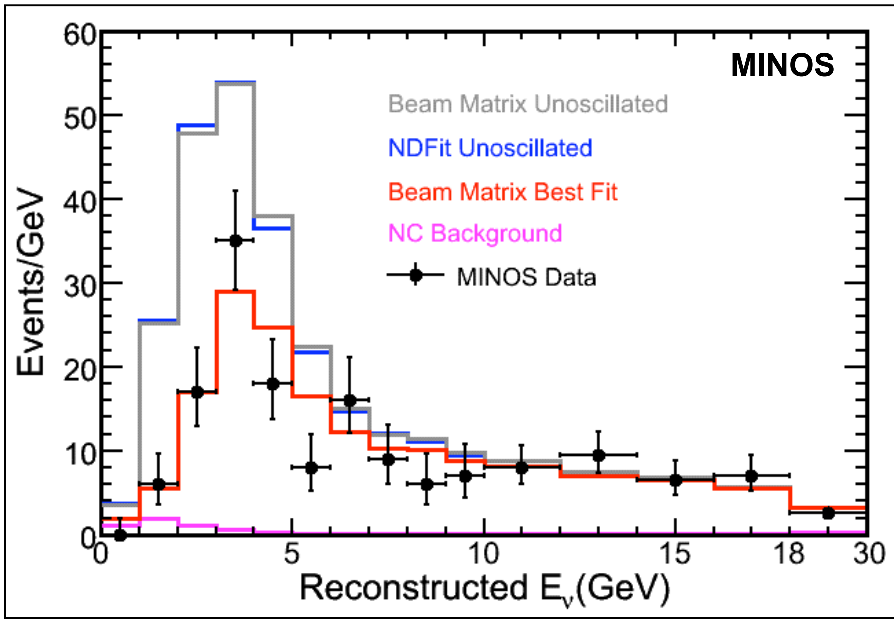
NuMI
beam line

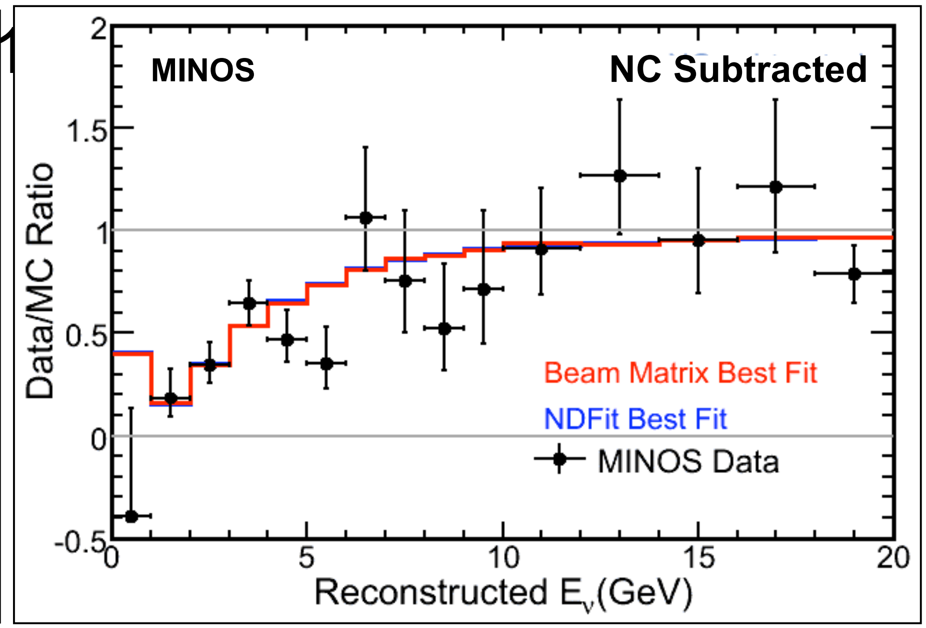
MINOS detector

- 8m octagonal tracking calorimeter
- 484 layers of 2.54 cm Fe plates
- 4.1 cm-wide scintillator strips with WLS fiber readout, read out from both ends
- 8 fibers summed on each PMT pixel; 16 pixels/PMT
- 25,800 m^2 of active detector planes
- Toroidal magnetic field <B> = 1.3 T
- Total mass 5.4 kT



MINOS Best-Fit Spectrum





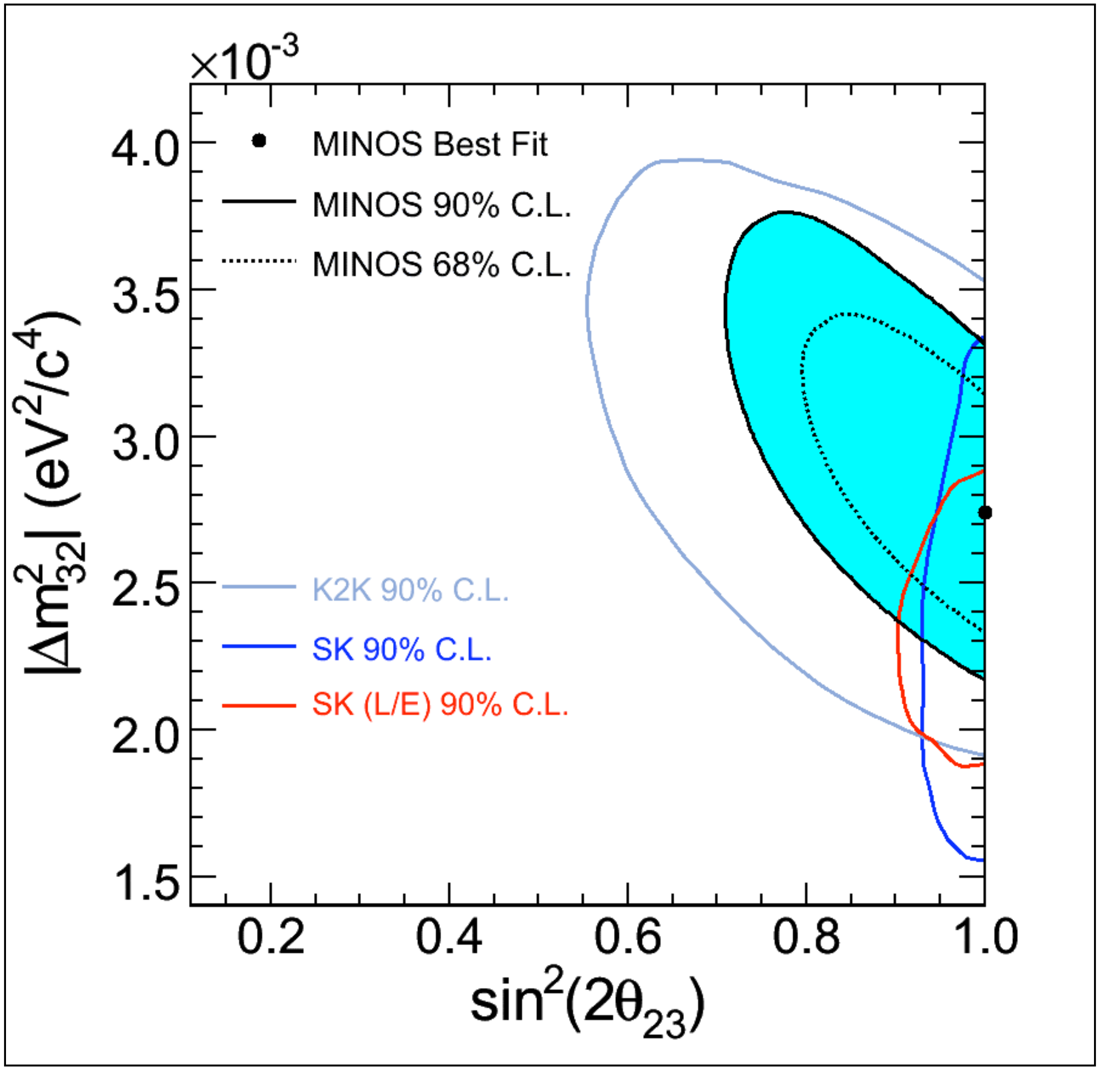
$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

$$\text{Normalization} = 0.98$$

Measurement errors are 1σ, 1 DOF

$$\chi^2 = \sum_{i=1}^{\text{nbins}} \left[2(e_i - o_i) + 2 o_i \ln(o_i / e_i) \right] + \sum_{j=1}^{\text{nsys}} \Delta s_j^2 / \sigma_{s_j}^2$$



×10^-3
MINOS Best Fit
MINOS 90% C.L.
MINOS 68% C.L.
K2K 90% C.L.
SK 90% C.L.
SK (L/E) 90% C.L.
4.0
3.5
3.0
2.5
2.0
1.5
0.2
0.4
0.6
0.8
1.0
|Δm²₃₂| (eV²/c⁴)
sin²(2θ₂₃)

The near future

Neutrino mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}$$

$\theta_{23} = (45 \pm 7)^\circ$

$\theta_{13} < 13^\circ$

$\delta = ?$

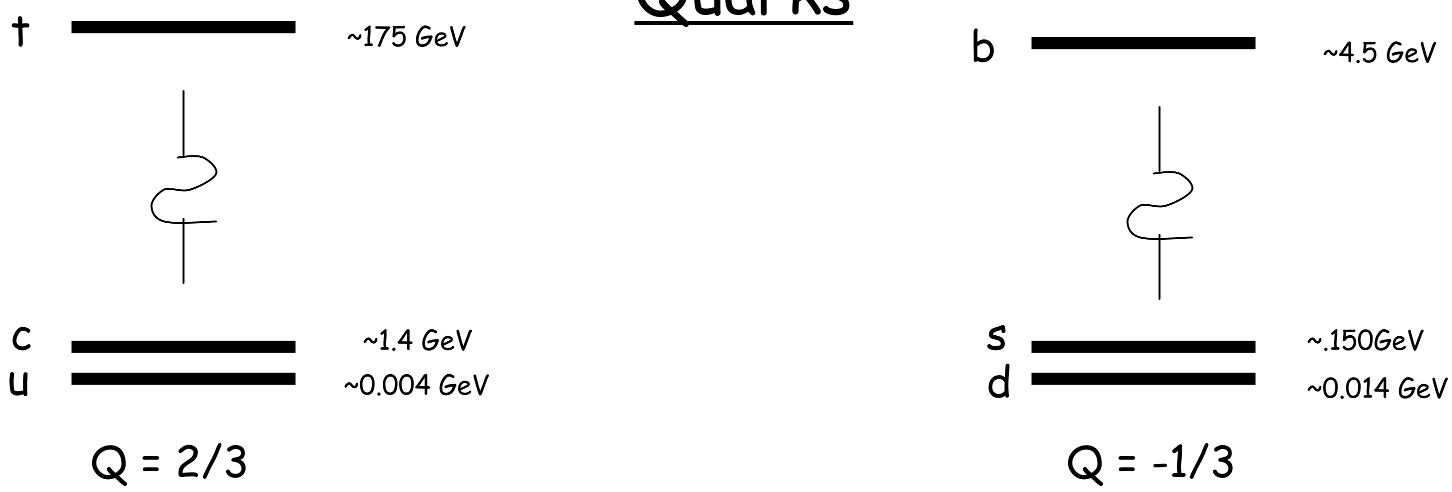
$\theta_{12} = (33.9^{+2.4}_{-2.2})^\circ$

$\alpha = ?$

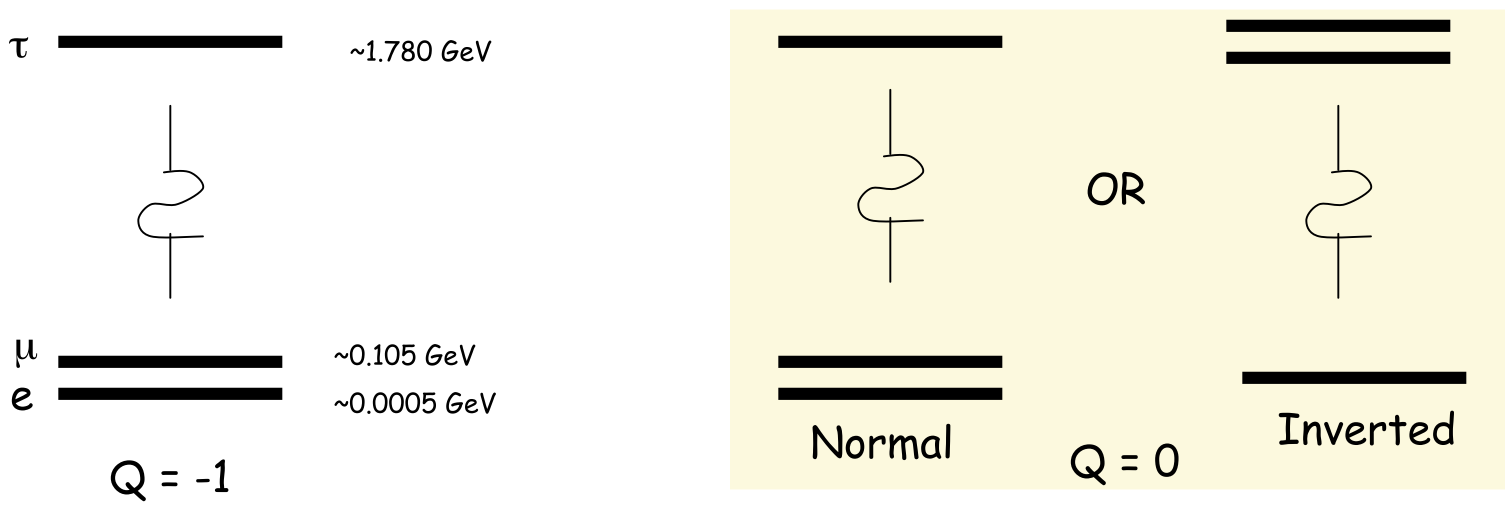
$\beta = ?$

Hierarchy Problem:

Quarks



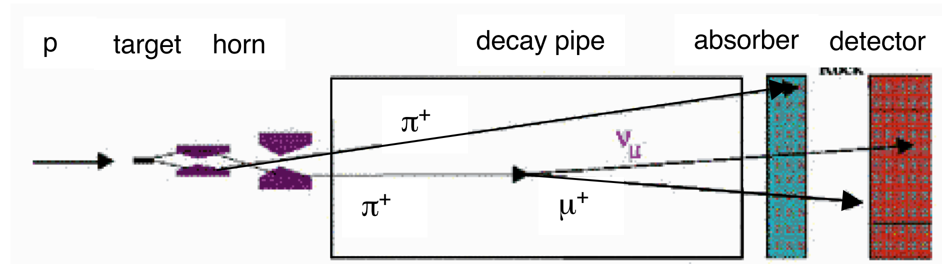
Leptons



Neutrinos

Measuring θ_{13}

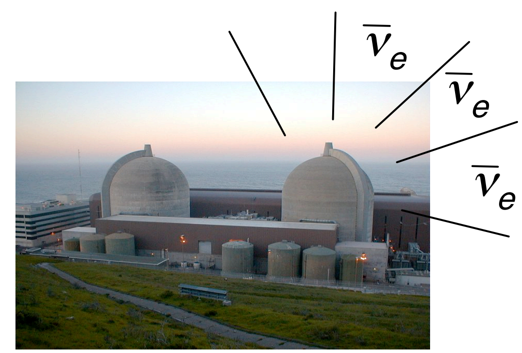
Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline *O(100 -1000 km),* matter effects present

Method 2: Reactor Neutrino Oscillation Experiment



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

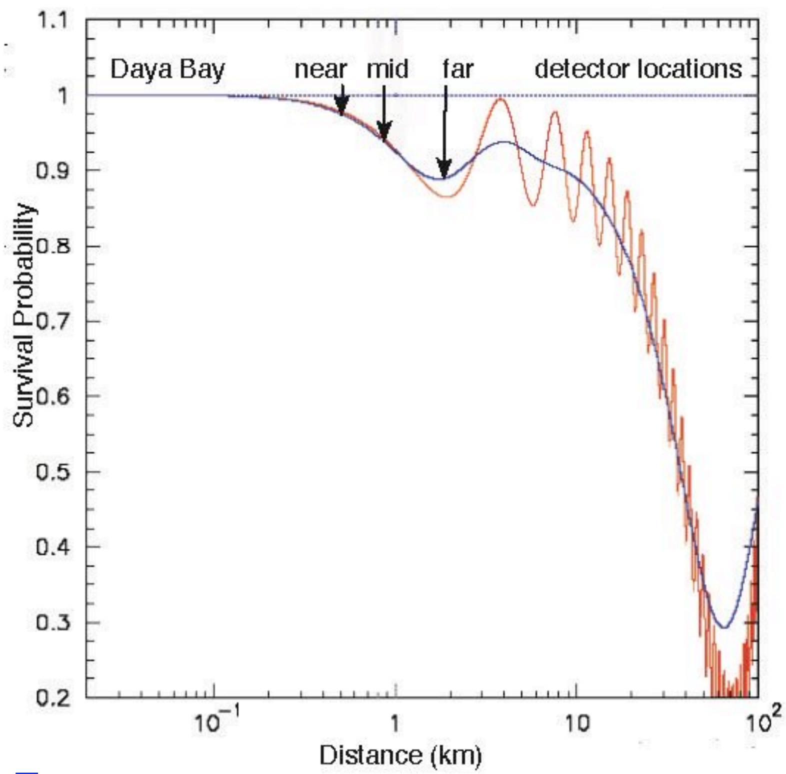
- disappearance experiment $\overline{\nu}_e \rightarrow \overline{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

Measuring θ_{13} with Reactor Antineutrinos

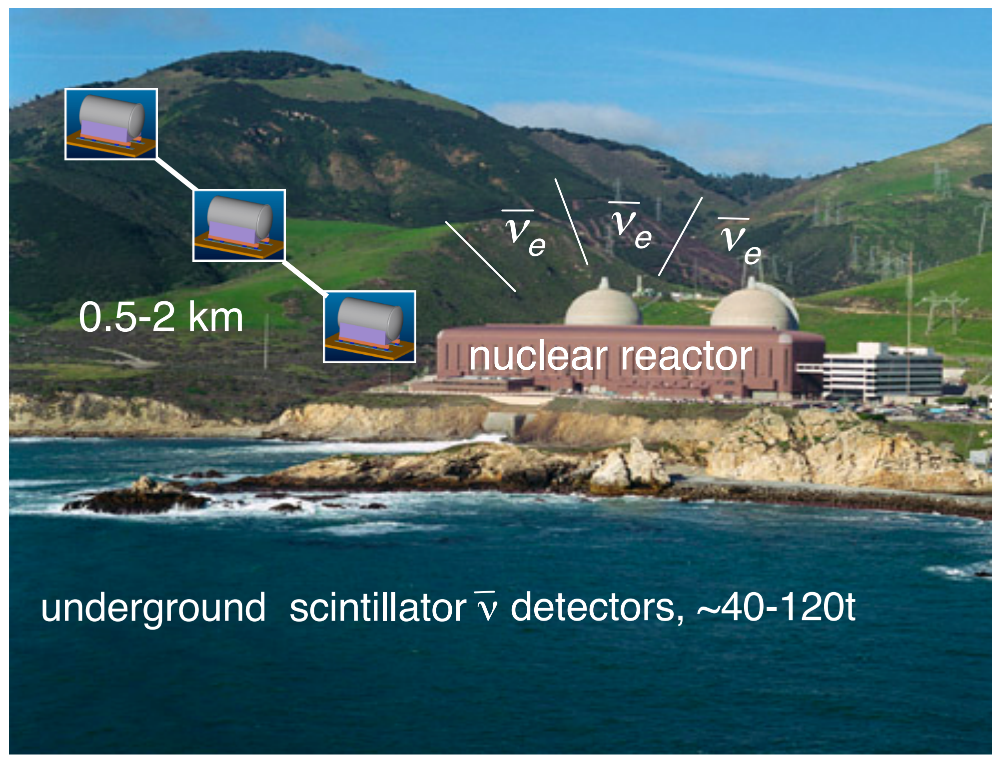
Precision Oscillation Measurement as a Function of Distance from Source

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

} θ_{13}



Relative $\bar{\nu}_e$ flux measurement at different distances.

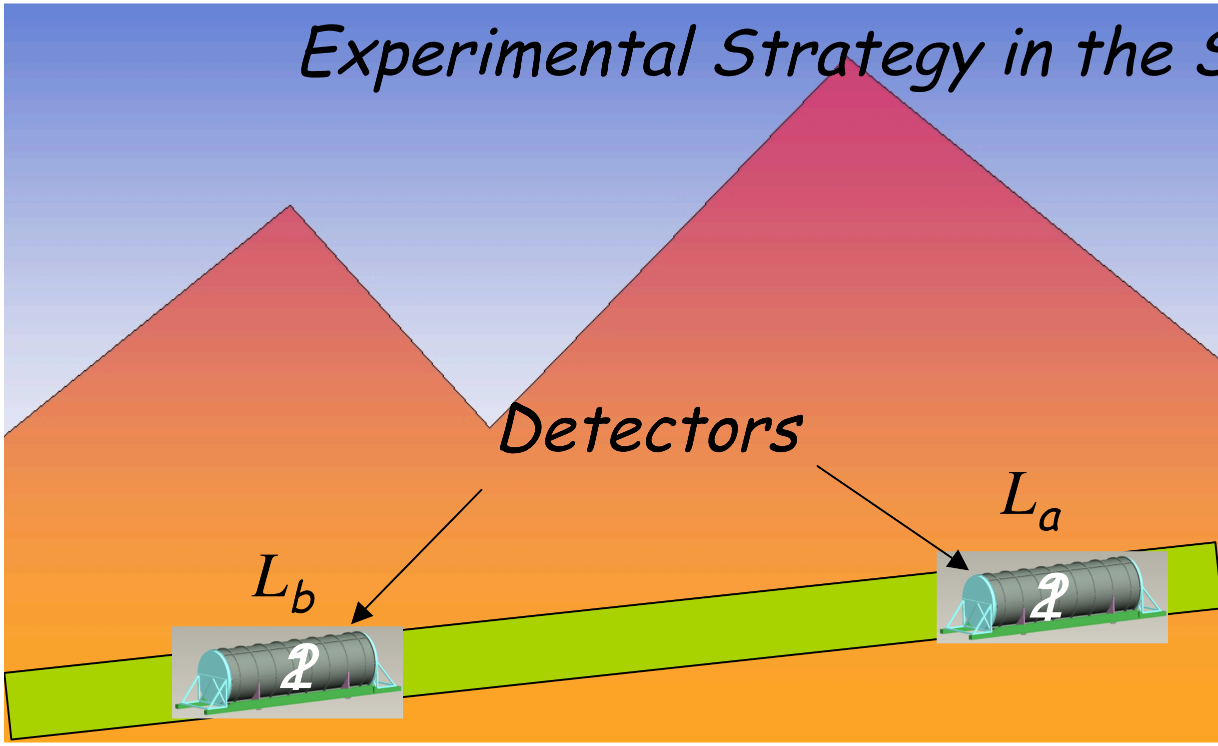


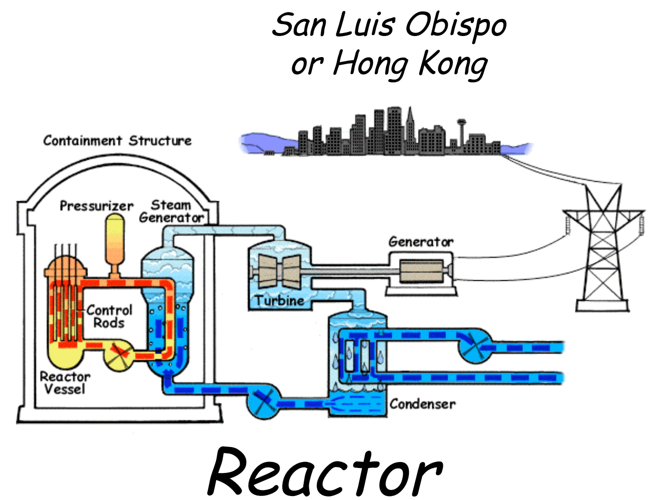
Event rate:

~1 event/GW/ton/day at 1km

Projected sensitivity: $\sin^2 2\theta_{13} \approx 0.01$

Experimental Strategy in the Simplest Case

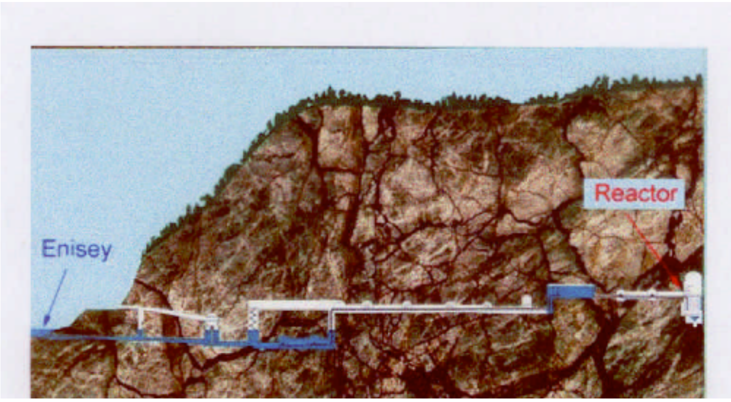


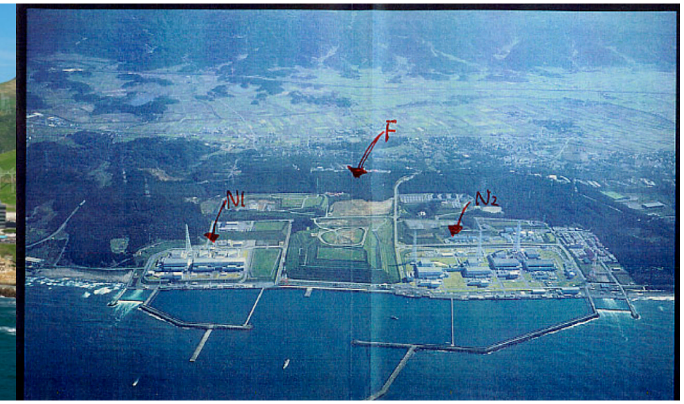


$$R_{1aA} = \frac{F_A}{4\pi L_a^2}\varepsilon_1(1-\delta_a)$$

$$\frac{R_{1aA}}{R_{2bA}}\frac{R_{2aB}}{R_{1bB}} = \frac{L_b^{\;4}}{L_a^{\;4}}\frac{(1-\delta_a)^2}{(1-\delta_b)^2} \approx \frac{L_b^{\;4}}{L_a^{\;4}}\left[1-2(\delta_a-\delta_b)\right]$$

$$(\delta_a-\delta_b) \approx \sin^2(2\theta_{13})\left[\sin^2(1.27\frac{\Delta m_{13}^2 L_a}{E}) - \sin^2(1.27\frac{\Delta m_{13}^2 L_b}{E})\right]$$

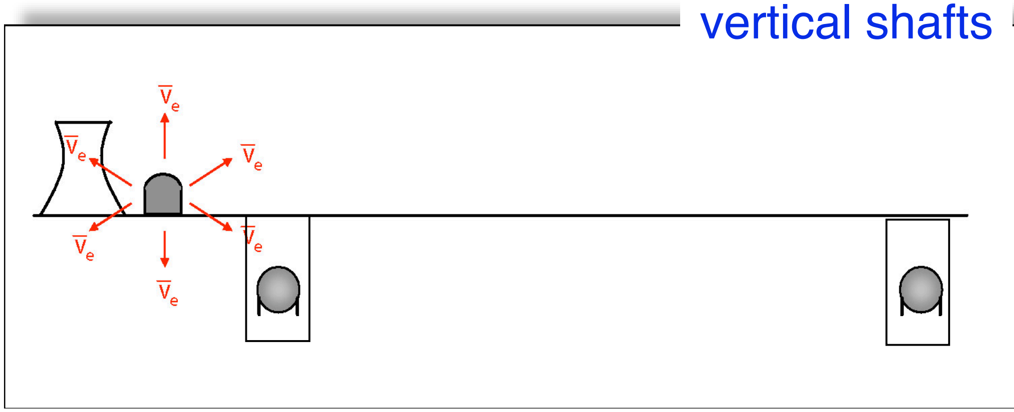


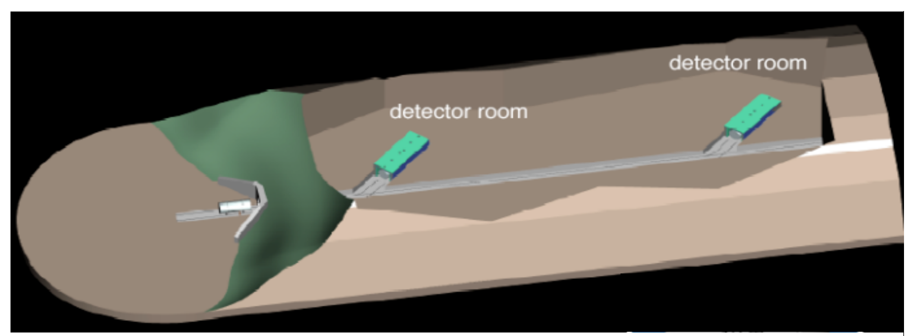
Proposals to Measure θ_{13} with Reactor Neutrinos



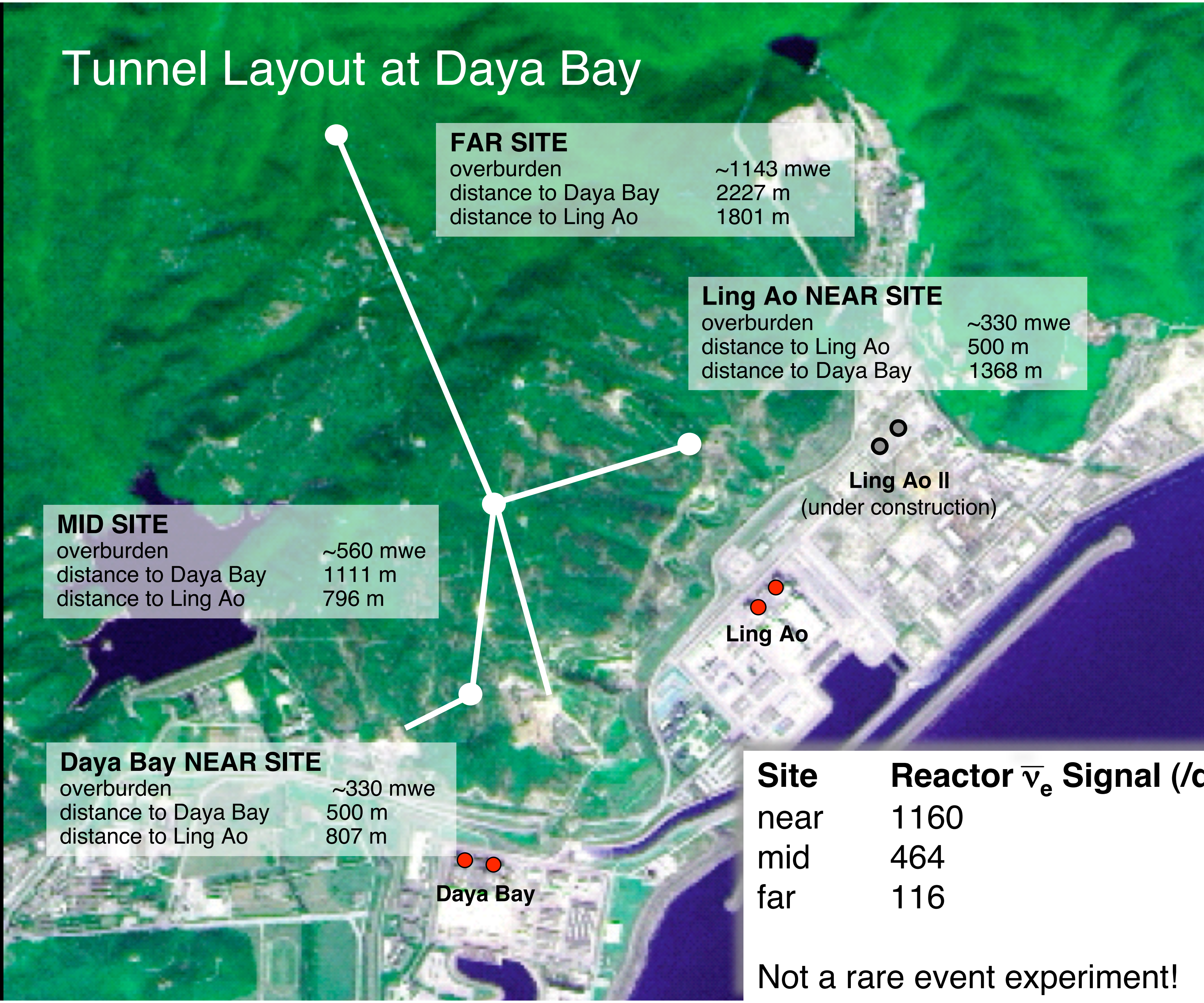
vertical shafts



horizontal tunnels



Tunnel Layout at Daya Bay

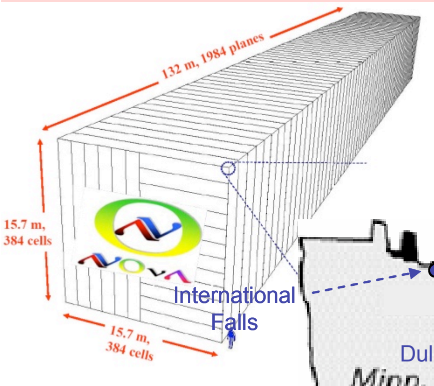


Site	Reactor $\overline{\nu}_e$ Signal (/day)
near	1160
mid	464
far	116

Not a rare event experiment!

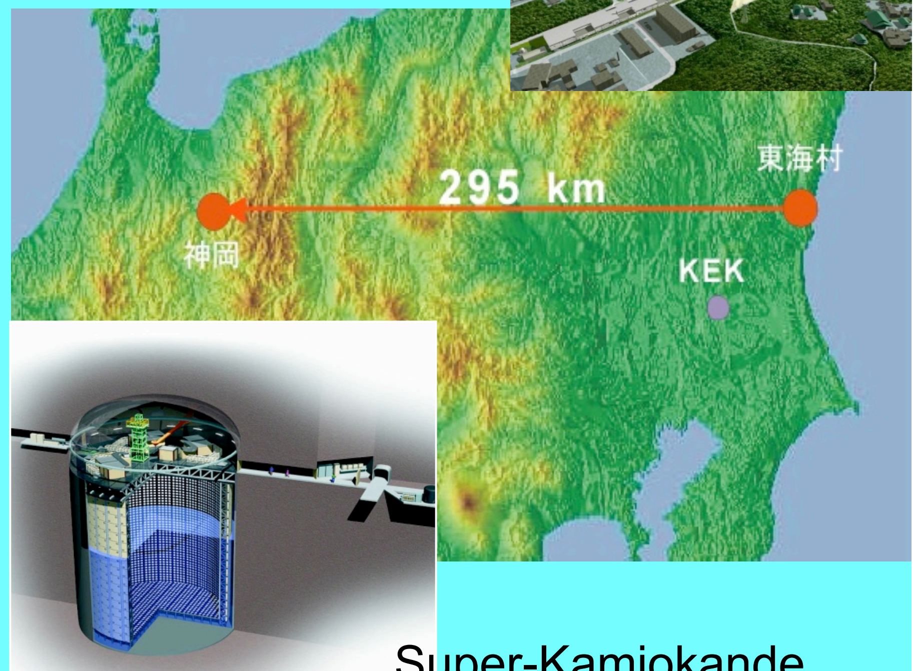
Near future LBL θ_{13} experiments

Nova



T2K

J-PARC



Super-Kamiokande

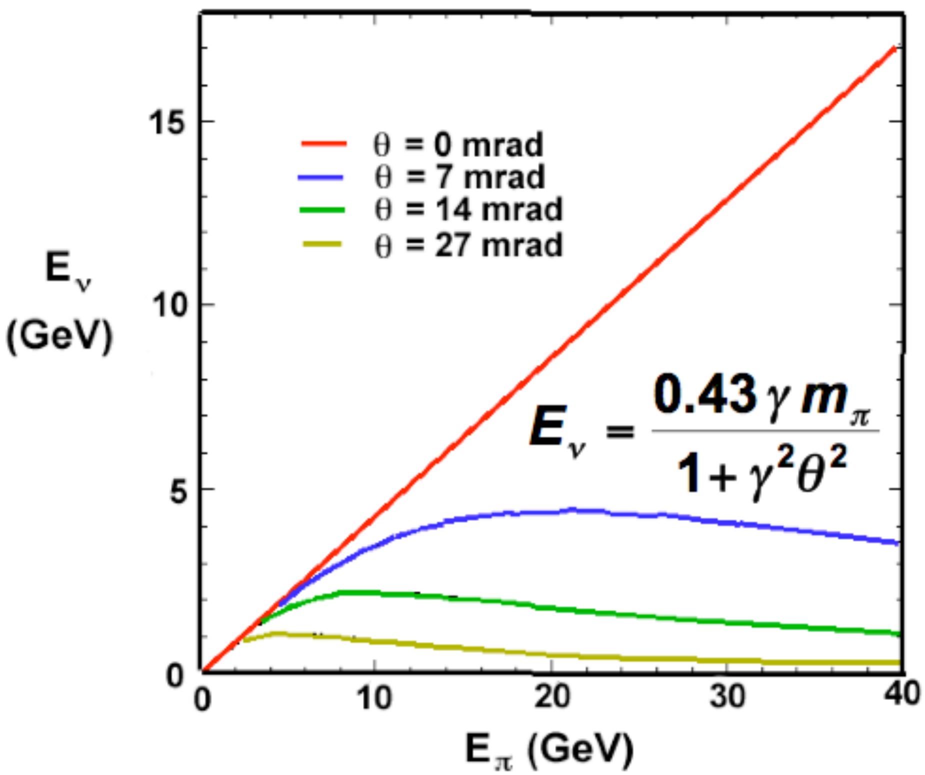
Acc/beamline ready

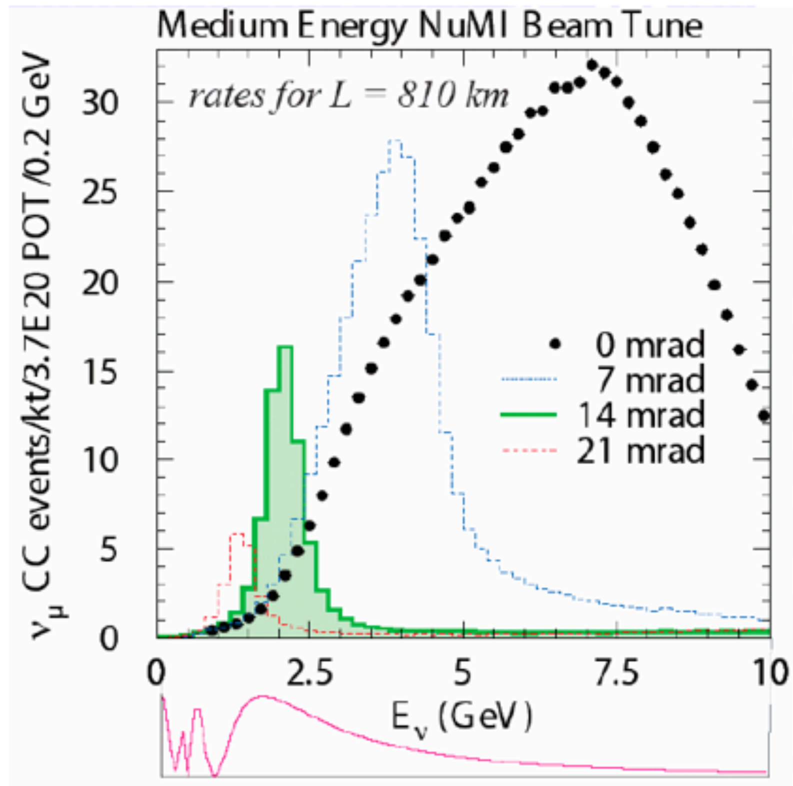
Detector need to be constructed

- Similar sensitivity
- Similar time scale

Acc/beamline under construction

Far detector ready


θ = 0 mrad
θ = 7 mrad
θ = 14 mrad
θ = 27 mrad
E_ν (GeV)
E_π (GeV)
$E_\nu = \frac{0.43\gamma m_\pi}{1+\gamma^2\theta^2}$
0
5
10
15
0
10
20
30
40


Medium Energy NuMI Beam Tune
rates for L = 810 km
ν_μ CC events/kt/3.7E20 POT/0.2 GeV
0 mrad
7 mrad
14 mrad
21 mrad
E_ν (GeV)
0
5
10
15
20
25
30
0
2.5
5
7.5
10

Three-neutrino oscillations

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$$

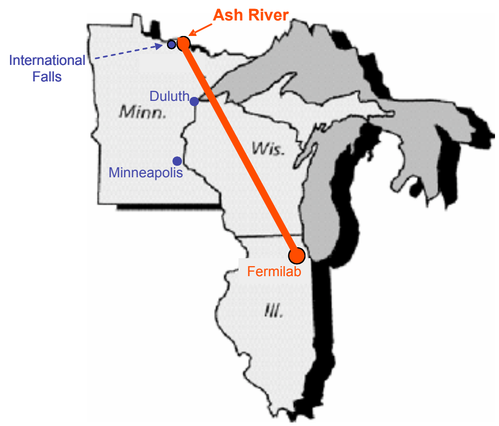
$$P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$$

$$P_3 = \quad J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$$

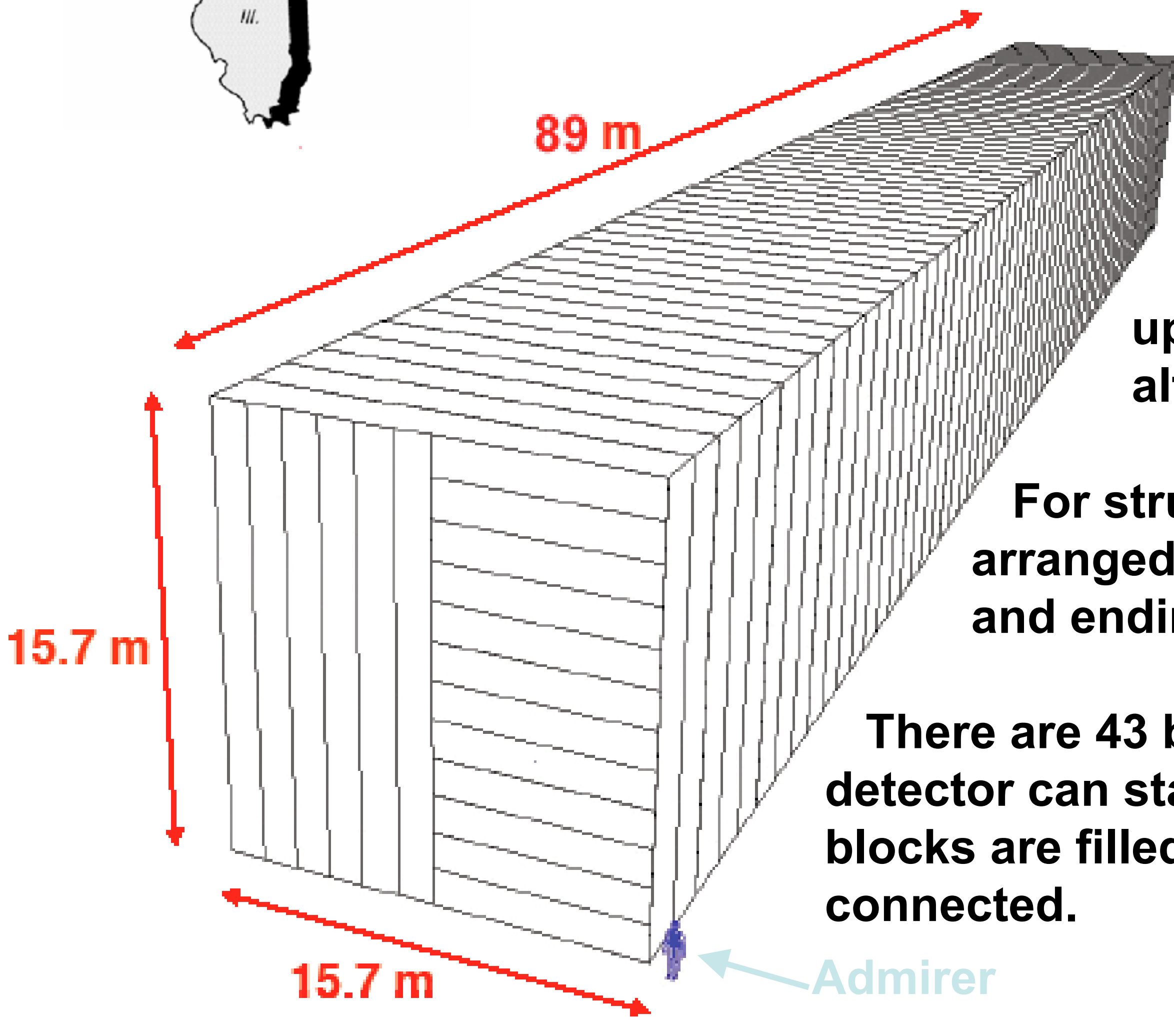
$$P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$$

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

$$\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$$



Nova



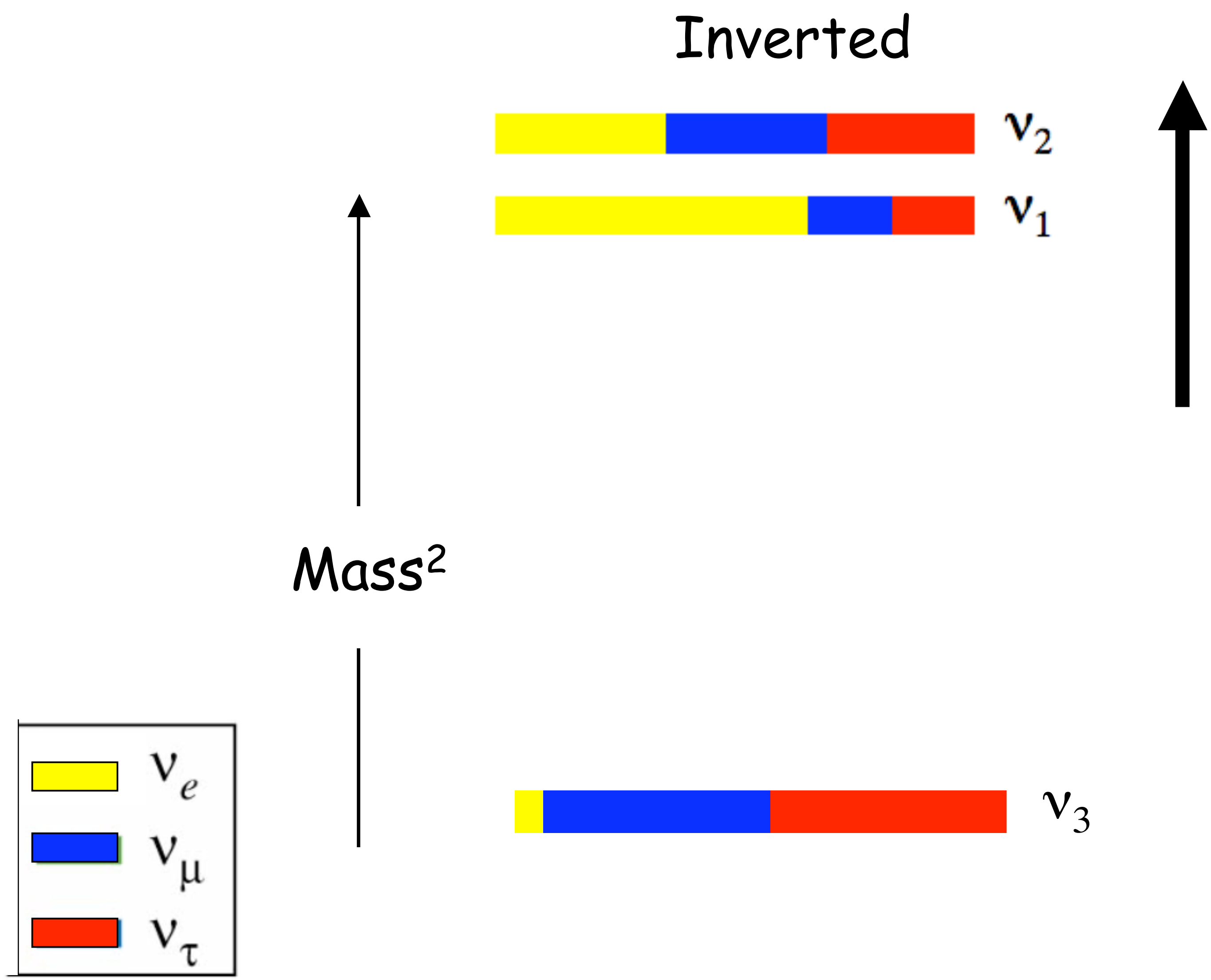
The cells are made from 32-cell extrusions.

12 extrusion modules make up a plane. The planes alternate horizontal and vertical.

For structural reasons, the planes are arranged in 31-plane blocks, beginning and ending in a vertical plane.

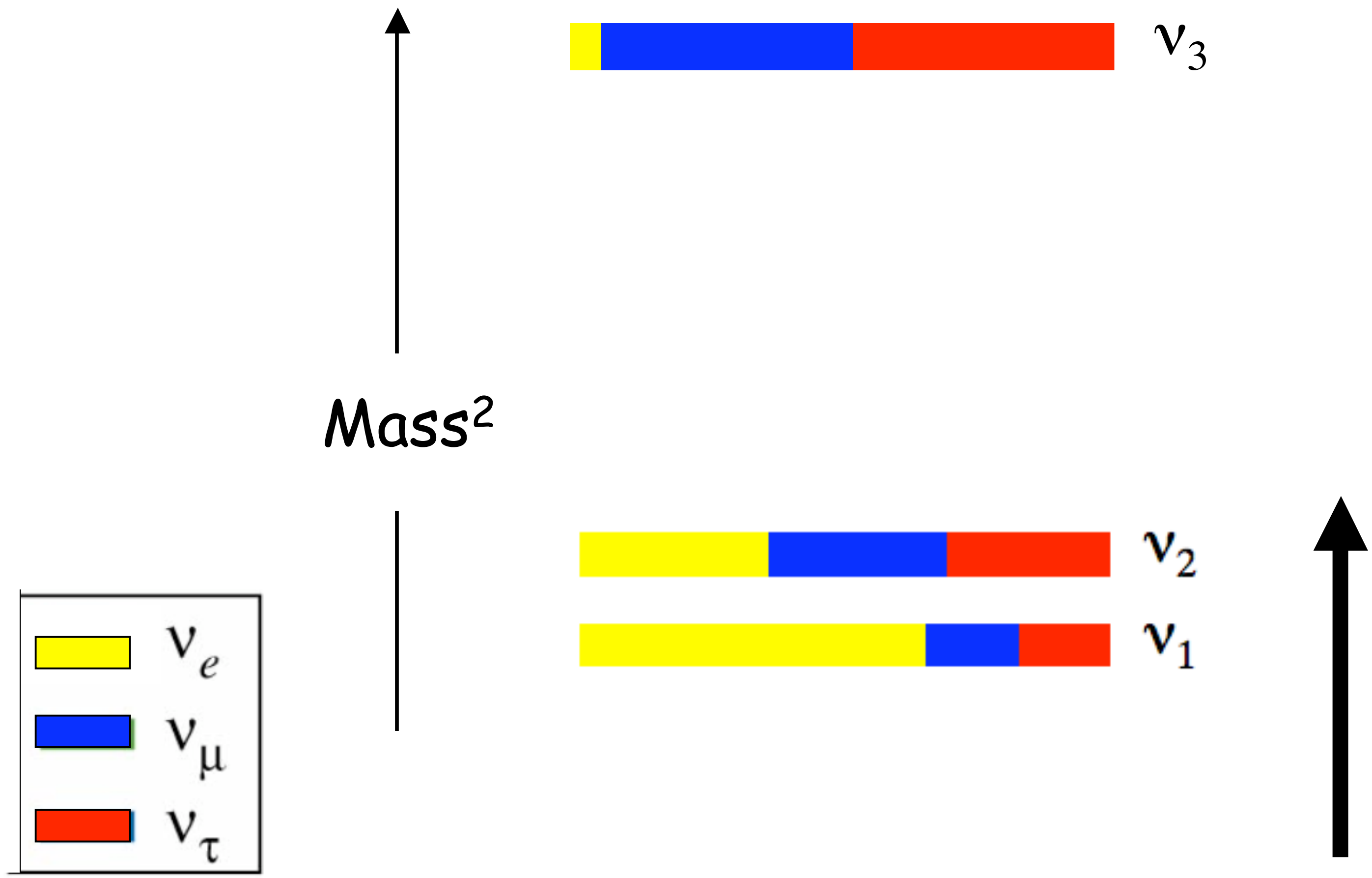
There are 43 blocks = 1333 planes. The detector can start taking data as soon as blocks are filled and the electronics connected.

Neutrino Mass



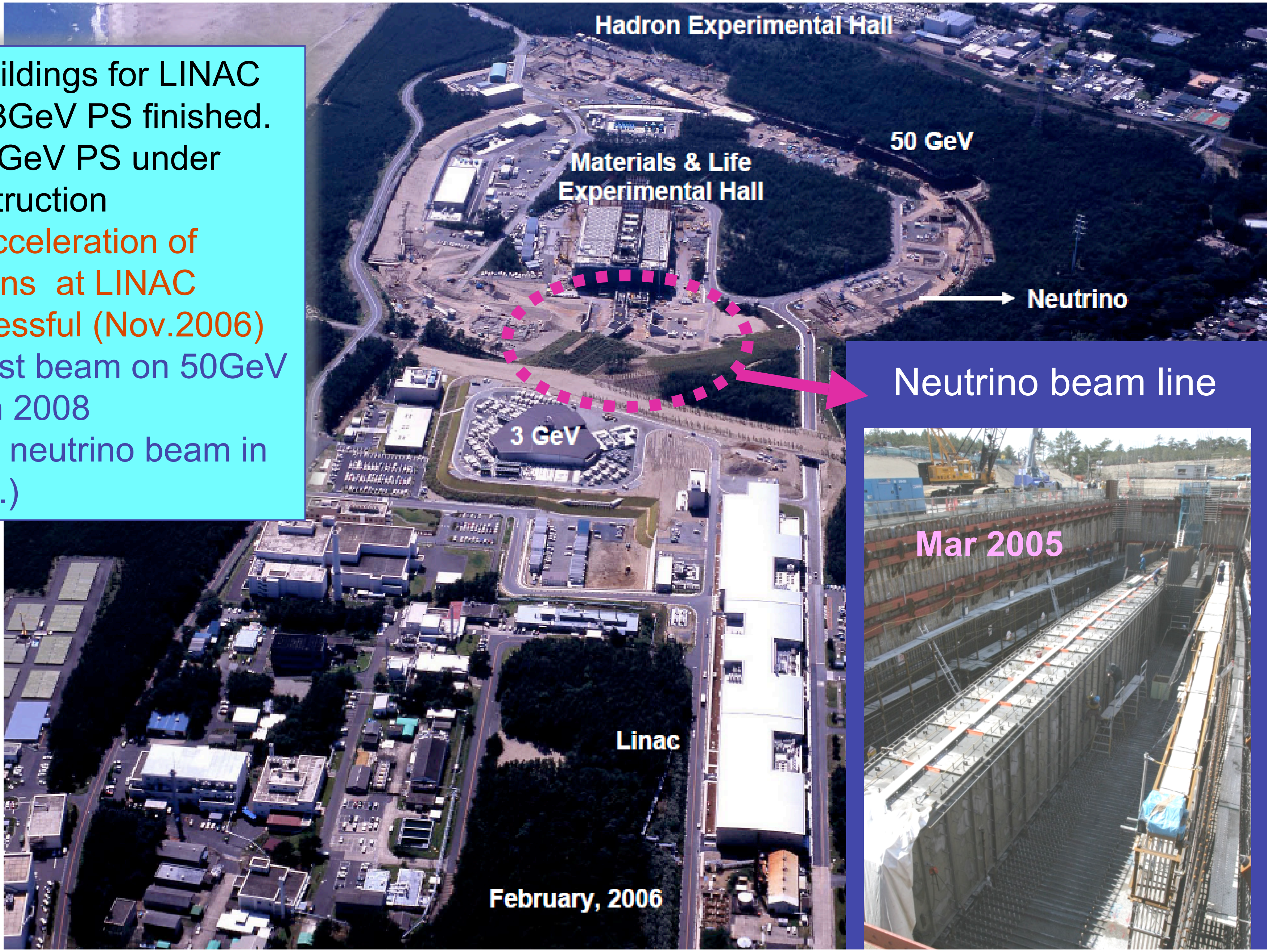
Neutrino Mass

Normal

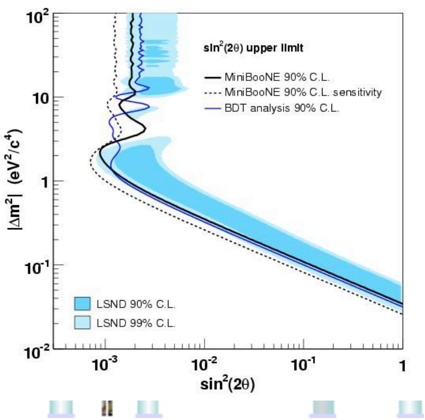


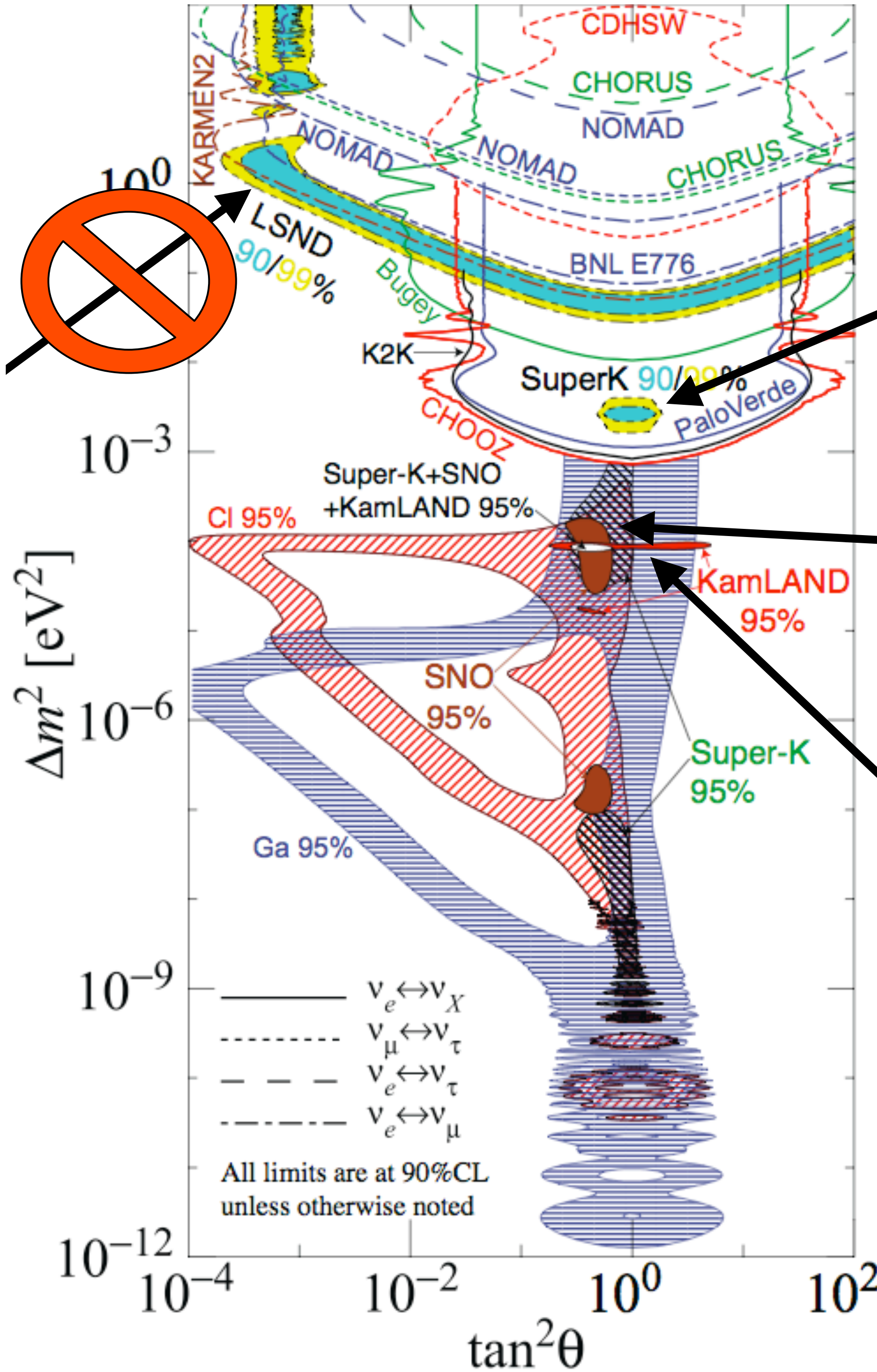
Status of J-PARC construction

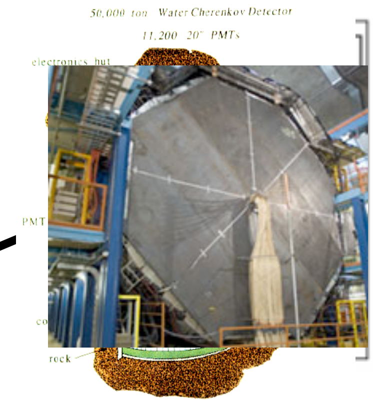
➔Buildings for LINAC and 3GeV PS finished.
➔50GeV PS under construction
➔ Acceleration of protons at LINAC successful (Nov.2006)
➔First beam on 50GeV PS in 2008
(First neutrino beam in 2009.)

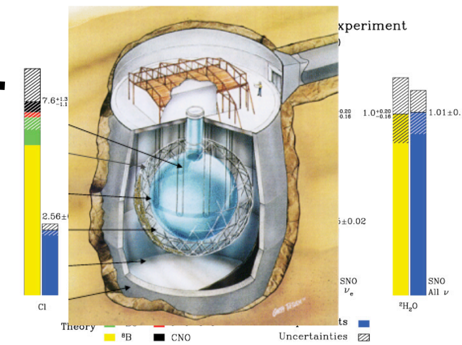


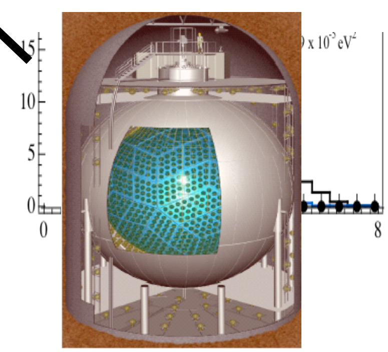
Neutrino Landscape

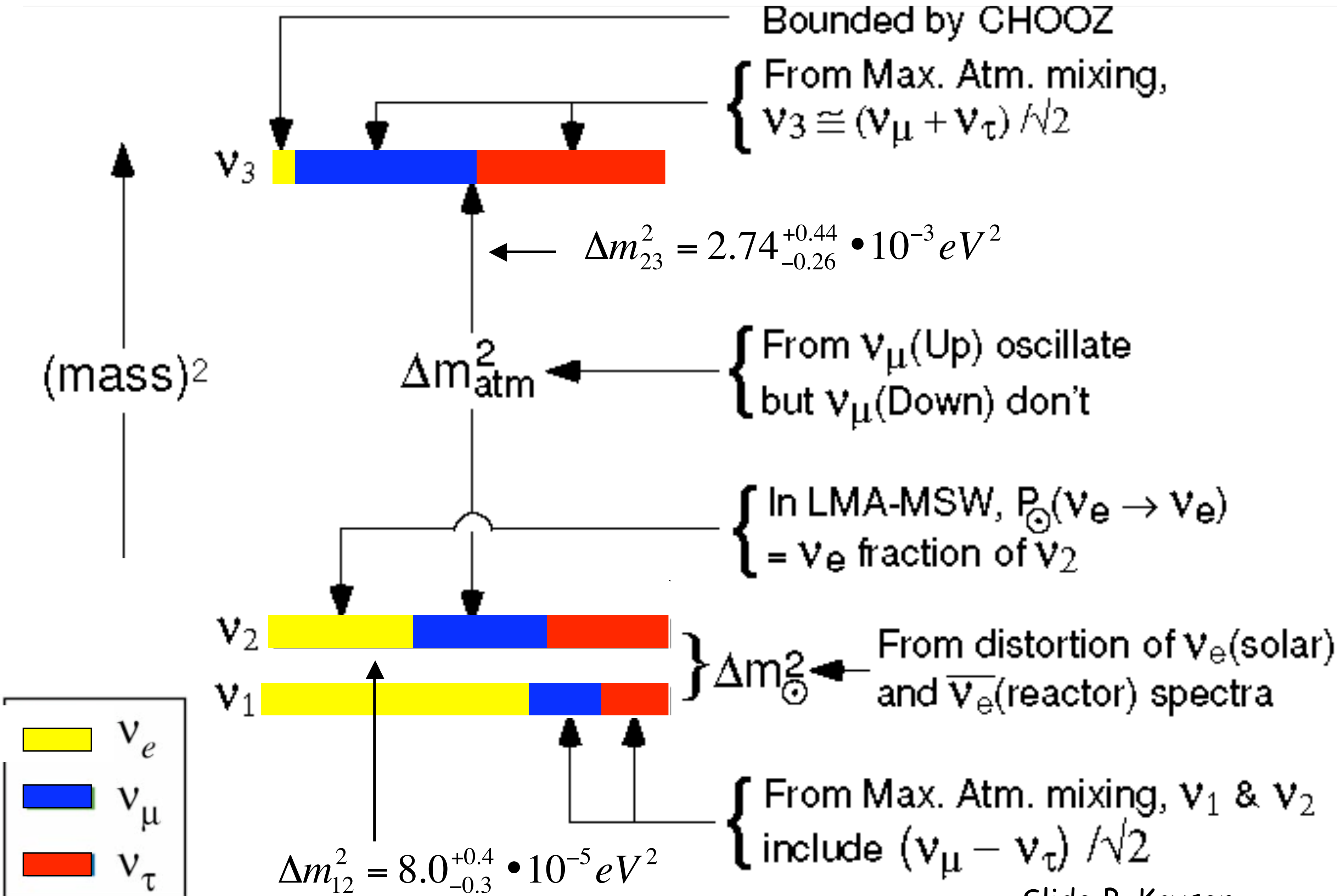












Slide B. Kayser